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The journal serves as a platform for knowledge exchange among scientists and practitioners working at the intersection of engineering, digital technologies, and systems thinking. Contributions are encouraged that integrate developments in information technology, cybersecurity, automation, robotics, artificial intelligence, sustainable development, and — as introduced in this issue — market synergy. Through theoretical and applied studies, the journal contributes to understanding emerging challenges and shaping progressive responses across interconnected scientific fields.

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Preliminary Design Evaluation of Solid-Propellant Rocket Engines

Mykola Bondarenko, Volodymyr Habrinets, Mykhailo Vorobei

Purpose. This article raises the issue of the necessity to develop methods for automated design evaluation of solid-propellant rocket engines at the early stages of missile development. **Design / Method / Approach**. The study is based on analytical models and empirical data derived from the development of numerous SREs by design bureaus, particularly Yuzhnoye State Design Office. It uses parametric analysis and optimization techniques, supported by statistical correction and verification against real-world motor data **Findings**. The article identifies critical parameters that influence solid-propellant rocket engines (SRE) efficiency and offers a computational framework for optimizing these parameters. The methodology significantly reduces the time required for preliminary assessments and allows for automated exploration of design alternatives. **Theoretical Implications**. This study contributes to the theoretical understanding of SRE performance modeling and optimization during conceptual design. It outlines how analytical dependencies can be constructed and refined based on engineering theory and empirical calibration. **Practical Implications**. The developed approach enables engineers to quickly generate and evaluate multiple engine design scenarios, improving the quality and speed of early decision-making in missile system development. **Originality / Value**. The work offers a practical and validated methodology for automated design evaluation of SREs, filling a gap in the early-stage engineering workflow. It is valuable to aerospace engineers, defense researchers, and developers of propulsion systems. **Research Limitations / Future Research**. The methodology focuses on typical SRE configurations and assumes statistical consistency across historical data. Future research may expand the models to incorporate novel materials, 3D-printed components, and adaptive control systems. **Article Type**. Methodological paper.

Keywords:

solid propellant rocket engines, automated design evaluation, preliminary design stage, parametric optimization, analytical performance modeling

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Мета. У цій статті підіймається питання необхідності розробки методів автоматизованої проєктної оцінки твердопаливних ракетних двигунів на ранніх етапах розробки ракетних комплексів. **Дизайн / Метод / Підхід**. Дослідження базується на аналітичних моделях та емпіричних даних, отриманих під час розробки численних твердопаливних ракетних двигунів (ТРД) конструкторськими бюро, зокрема ДП «КБ «Південне». Застосовано методи параметричного аналізу та оптимізації з подальшою статистичною корекцією та перевіркою на основі реальних даних двигунів. **Результати**. У статті визначено ключові параметри, що впливають на ефективність ТРД, та запропоновано обчислювальну структуру для їх оптимізації. Методика суттєво скорочує час, необхідний для попередньої оцінки, та дозволяє автоматизувати дослідження альтернативних варіантів конструкції. **Теоретичне значення**. Це дослідження сприяє розвитку теоретичного розуміння моделювання та оптимізації характеристик ТРД на концептуальному етапі. Показано, як аналітичні залежності можуть бути побудовані та уточнені на основі інженерної теорії та емпіричного калібрування. **Практичне значення**. Розроблений підхід дозволяє інженерам швидко формувати та оцінювати декілька варіантів конструкції двигунів, підвищуючи якість і швидкість прийняття рішень на ранніх етапах створення ракетних систем. **Оригінальність / Цінність**. Робота пропонує практичну та верифіковану методику автоматизованої оцінки проєктних рішень для ТРД, що заповнює прогалину в процесі раннього інженерного проєктування. Вона є цінним ресурсом для аерокосмічних інженерів, фахівців з оборонних технологій і розробників рушійних установок. **Обмеження дослідження / Майбутні дослідження**. Методика орієнтована на типові конфігурації ТРД і базується на припущенні статистичної узгодженості історичних даних. У майбутньому дослідження можуть бути розширені з урахуванням нових матеріалів, компонентів, виготовлених на 3D-принтерах, і адаптивних систем управління. **Тип статті**. Методологічна стаття.

Ключові слова:

твердопаливні ракетні двигуни, автоматизована проєктна оцінка, етап початкового проєктування, параметрична оптимізація, аналітичне моделювання характеристик

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Solid-propellant rocket engines (SREs) play a fundamental role in the design and performance of modern missile systems. Their effectiveness directly impacts the range, payload capacity, stability, and overall success of the vehicle in achieving mission objectives. However, the process of designing and evaluating SREs remains complex and time-consuming, often requiring the involvement of multiple domain-specific experts in propulsion, thermodynamics, internal ballistics, structural integrity, and materials engineering. This challenge becomes particularly acute during the preliminary design stage, when multiple configuration options must be rapidly evaluated under time and resource constraints (Glazkov et al., 2018). To address this problem, an automated methodology has been developed for the rapid assessment of key performance parameters of SREs used in missile systems. This approach enables engineers to conduct computational evaluations of dozens or even hundreds of design options without the need for full-scale calculations or consultations with specialized departments. The proposed methodology is built upon a combination of analytical models, empirical correlations, and statistical data obtained from previously developed SREs. The system is designed for application in a wide range of missile classes - from tactical and operational-tactical missiles to intercontinental ballistic missiles and space launch vehicles. It allows the user to determine optimal design parameters such as fuel mass, motor diameter, chamber pressure, nozzle expansion ratio, and burn time under given constraints. The methodology significantly accelerates the conceptual design process by replacing labor-intensive manual calculations with instant, software-driven evaluations.

This paper presents the theoretical foundations, structure, and implementation of the automated evaluation methodology, as well as its validation through comparisons with real-world designs. It also explores the applicability of the method to various SRE configurations and outlines its practical value for engineers engaged in early-stage missile development projects.

Purpose

The purpose of this study is to develop and present an automated methodology for evaluating the key performance parameters of SREs during the early stages of missile system design. The work aims to streamline the process of preliminary assessment by reducing reliance on manual calculations and minimizing the need for consultations with multiple domain experts. Through the integration of analytical models, statistical data, and design experience, the proposed approach enables rapid exploration of multiple SRE configurations under given technical and operational constraints.

This methodology is intended to assist engineers and designers in selecting optimal motor parameters - such as propellant mass, chamber pressure, burn time, and nozzle expansion ratio - that maximize overall missile efficiency according to ballistic, dimensional, mass, and reliability criteria. It also supports the identification of trade-offs and limitations that arise during configuration selection. The study emphasizes the need for fast and reliable tools that can support high-quality decision-making at the conceptual stage of missile development.

Data and Methods

The development of the automated evaluation methodology is based on a combination of theoretical models, empirical data, and statistical analysis of previously developed SREs. The primary data sources include engineering documentation, performance archives, and statistical datasets from missile development projects carried out by Yuzhnoye State Design Office and other aerospace institutions (Kirichenko et al., 2016).

The methodology integrates the following key elements:

1. *Analytical Modeling*. Fundamental equations from internal ballistics, thermodynamics, structural mechanics, and gas dynamics were used to describe the core physical processes within SREs. These models serve as the backbone for calculating performance metrics such as chamber pressure, specific impulse, and structural loads.

2. *Empirical Correlation*. Analytical results are refined using empirical correction factors derived from historical test data and operational experience. These corrections enhance the reliability of predictions across a wide range of design cases.

3. *Effectiveness Assessment*. The effectiveness of precision strikes was assessed by examining the precision, speed, and impact of multiple launch rocket systems in various combat scenarios, using available data and reports on their use in military engagements.

4. *Literature Review*. A review of open-source publications, technical documents, and scientific research on the development, deployment, and operational use of HIMARS and similar systems in combat (Bondarenko et al., 2024).

5. *Data Synthesis*. Data gathered from military reports, news articles, and technical studies were synthesized to draw conclusions about the strategic and operational implications of multiple launch rocket systems in modern warfare.

Background and Motivation

The design of SREs for missile systems is a highly complex engineering task. It involves the simultaneous consideration of numerous parameters, including internal ballistics, thermal regimes, structural integrity, and aerodynamic performance. Traditionally, this process requires the involvement of a large number of specialists across multiple disciplines and consumes considerable time and resources, especially during the conceptual phase of development.

At the early stages of missile design, engineers are often tasked with evaluating a wide range of possible configurations for SRMs under tight time constraints. The ability to rapidly assess the performance of dozens or even hundreds of variants become critical to the overall efficiency of the design process. In such cases, traditional calculation methods become inefficient, and the lack of automation leads to delays and decision-making bottlenecks.

The need for a fast, reliable, and reasonably accurate solution prompted the development of an automated methodology capable of providing preliminary assessments of SRM performance on a personal computer. This methodology is specifically intended to support design decisions during the initial project phases, where rough but informative estimations can significantly influence the direction of further engineering work. By automating the estimation of key parameters - such as thrust, chamber pressure, burn time, and motor geometry - this approach allows a single engineer to perform complex analyses in a fraction of the time required by manual or segmented workflows. The methodology presented here is based on practical experience accumulated during the development of numerous SREs by Yuzhnoye State Design Office (Ukraine) and is supported by verified empirical and statistical data collected over several decades (Kirichenko et al., 2014).

Literature Review

As part of the present work, an analysis and systematic review of recent publications directly and indirectly related to the preliminary design evaluation and development of solid-propellant rocket engines was carried out. The review covered both classical and applied studies of internal ballistics and structural design, as well as contemporary numerical and experimental investigations – for example, studies on internal ballistics and mathematical modelling of combustion processes (Kositsyna et al., 2021; Tian et al., 2021; Rashkovskiy & Yakush, 2020), investigations of nozzle insert erosion and behaviour (Cang & Wang, 2024; Almayas et al., 2021), numerical studies of ignition/transient processes and gas dynamics of combustion products (Wentao et al., 2024; Deyou et al., 2024), and works on grain regression modelling, mesoscale descriptions of AP/HTPB combustion, and grain-shape optimization (Rashkovskiy et al., 2020; Combustion & Flame, 2023; Li et al., 2024). Studies addressing the energetic characteristics of propellant components and thermal protection materials were also examined (Wang et al., 2025; Mochonov et al., 2020).

Despite the availability of modern publications from 2020 – 2025, the review indicates that methodologies are dispersed across multiple approaches – experiments, numerical simulation, empirical correlations, and materials science studies – with individual works typically addressing only specific aspects (e.g., nozzle erosion or mesoscale combustion) rather than providing a comprehensive solution for the preliminary design evaluation of a propulsion system as an integrated case (Galletly & Verstraete, 2025; Teng et al., 2025). The objective of this paper is therefore to raise the issue of creating a unified algorithm: to collect diverse cases and methods from recent literature, to synthesize empirical relationships and numerical approaches, and to combine them into a single, reproducible methodology for the preliminary design evaluation of solid-propellant rocket engines that closes identified gaps and improves the reproducibility and accuracy of calculations (Chen et al., 2024).

Structure of the Automated Evaluation Methodology

The proposed methodology is designed to estimate the key parameters of SREs at the conceptual design stage using a combination of analytical models, empirical corrections, and optimization algorithms. Its structure reflects the interconnected nature of rocket design, where performance, geometry, and manufacturing constraints must be considered simultaneously. The methodology comprises the following main components.

Input Data and Design Variables

The evaluation begins with the input of baseline design parameters, including: motor diameter (D); propellant mass (ω); chamber pressure (P_k); nozzle expansion ratio (ζ); burn time (t_p). These parameters are treated as variable within defined ranges based on the target missile class. Additionally, constraints related to maximum diameter, integration volumes, and separation conditions are considered (Bondarenko & Habrinets, 2023).

Optimization Criteria

The methodology allows optimization according to several possible criteria, including: external ballistics (e.g., maximizing range or payload mass); mass efficiency (e.g., minimizing launch mass); dimensional constraints (e.g., minimizing length or diameter); reliability and safety; economic or manufacturing feasibility; multiple criteria can be combined using weighting factors or applied in stages.

Analytical Models and Dependencies

Each SRE parameter is calculated using core equations derived from the theory of internal ballistics, thermodynamics, structural mechanics, and empirical design practice. Key performance characteristics include: specific impulse in vacuum (I_{sp}); maximum chamber pressure ($P_k$max); propellant mass flow rate ($\dot{m}$); nozzle throat erosion (Δd_t); total motor length and structural mass. The models are corrected using statistical data from legacy SRE designs developed by Yuzhnoye SDO and other aerospace institutions. These corrections ensure applicability across a wide design space and improve prediction reliability (Ushkin, 2016).

Design Constraints and Feasibility Checks

The tool checks whether selected configurations are feasible given geometric limitations, required performance levels, and production capabilities. For example, the method accounts for: constraints on the combustion rate and chamber pressure for safe stage separation; compatibility with available nozzle and casing technologies; integration requirements with launch platforms.

Output and Interpretation

The methodology produces a full set of output parameters for each configuration, including: thrust curve and impulse; pressure-time history; mass breakdown (propellant, structure, nozzle); dimensional layout; thermal and structural load estimates. These outputs support rapid decision-making and allow comparison across multiple variants, enabling the identification of optimal configurations.

Parameter Ranges and Application Domains

The automated evaluation methodology has been developed to support a broad spectrum of SRM configurations used in various classes of missile systems. These range from tactical and operational-tactical missiles to intercontinental ballistic missiles (ICBMs) and space launch vehicles. To ensure versatility and applicability, the methodology incorporates parameter ranges representative of real-world engineering practice (Bondarenko et al., 2025).

Tactical and Operational-Tactical Missiles

For short- and medium-range missile systems, the methodology supports the following parameter ranges: motor diameter 0.25–0.9 m; propellant mass 150–4500 kg; chamber pressure 3.9–14.7 MPa; burn time 10–50 s; nozzle expansion ratio: 2.5–10.

A typical SRM for such missiles is shown on Fig. 1. Key features of this SRM: composite propellant; propellant charge is bonded to the motor casing; the casing is made of high-strength steel; fixed nozzle. These motors are typically designed with stationary nozzles, composite solid propellants, and steel casings. Their configurations emphasize compactness, reliability, and ease of integration into mobile launch platforms.

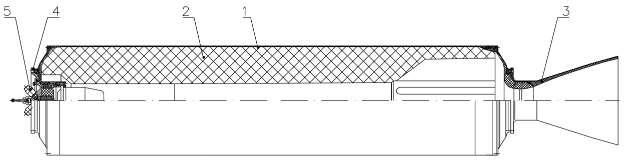

Figure 1 – SRM design scheme: 1 - motor casing, 2 - structurally-bonded solid propellant grain, 3 - nozzle assembly, 4 - forward dome, 5 - ignition system (Source: Authors)

Intercontinental Ballistic Missiles and Space Launch Missiles

For large-scale propulsion systems, the methodology accommodates extended ranges of input parameters: motor diameter 0.9–2.5 m; propellant mass 2100–65000 kg; chamber pressure 3.92–11.77 MPa; burn time 10–100 s; nozzle expansion ratio: 2–10.

These motors often feature composite or wound plastic casings (cocoon-type), bonded grain designs, and movable nozzles for thrust vector control using hydraulic or electric actuators.

Modular Applicability

The structure of the methodology allows it to be adapted to other classes of SRMs with minimal modification. This includes: upper stages with lower thrust and longer burn durations; launch boosters requiring high-thrust, short-duration performance; experimental configurations with novel grain geometries or additive-manufactured components.

The system is thus applicable at multiple stages of the development pipeline – from conceptual studies to early-stage trade-off analysis – and can be customized to match the evolving needs of missile programs.

Analytical Models and Statistical Calibration

The core of the automated evaluation methodology is built upon a series of analytical models describing the thermodynamic, ballistic, and structural behavior of SRMs. These models are augmented with statistical corrections derived from empirical data obtained through the development and testing of multiple SRM configurations, primarily at Yuzhnoye State Design Office (Ushkin et al., 2016).

Energy Performance Models

The specific impulse in vacuum (I_{sp}-vac) is a fundamental metric for evaluating propulsion efficiency. In this methodology, the ideal thermodynamic impulse is modeled as a function of nozzle expansion ratio (ζ) and chamber pressure (P_k), calibrated for various propellant formulations:

$$I_{sp}^{ideal} = f(\zeta, P_k). \quad (1)$$

Losses due to nozzle efficiency, flow separation, and erosion are introduced via empirical correction terms, yielding a realistic prediction of the effective specific impulse:

$$I_{sp}^{real} = I_{sp}^{ideal} - \Delta I_{losses}. \quad (2)$$

Parameters such as aluminum content (q_m), throat-to-exit area ratio, and nozzle contour length are also accounted for, especially when assessing high-performance composite propellants.

Internal Ballistic Models

The internal ballistic behavior of SRMs is a key factor in determining pressure stability, thrust generation, and structural loading. In the proposed methodology, chamber pressure is estimated under nominal and off-nominal conditions using analytical relationships supplemented with statistically derived correction factors.

The baseline chamber pressure P_k is treated as a design input, reflecting mission-specific requirements. However, due to variations in geometry, temperature, and burn rate characteristics, the actual maximum pressure P_k^{max} may exceed this nominal value.

To estimate P_k^{max}, a multi-parameter expression is used:

$$P_k^{max} = P_k \cdot f(\Delta \mathrm{S}, \nu, \alpha_t, \Delta \mathrm{T}, \delta_{sl}, \Delta \mathrm{u}), \quad (3)$$

where ΔS – maximum deviation of the burning surface, m^2; ν – pressure exponent in the burn rate law, dimensionless; α_t – temperature sensitivity coefficient, 1/K; ΔT – operational temperature deviation, K; δ_{sl}, Δu – statistical factors reflecting real-world variability, dimensionless. These parameters capture both design-driven and environmental variations influencing pressure buildup during operation.

When geometric characteristics of the grain are known, the deviation ΔS_{max} can be approximated as a function of grain elongation λ_z. The following empirical formula, based on regression analysis of design data, is applied:

$$\Delta S_{max} = -0.0055 \cdot \lambda_z^2 \cdot 0.1387 \cdot \lambda_z + 8.5875\,. \quad (4)$$

This expression reflects typical surface variation behavior in bonded charge configurations and provides a reliable estimate of the expected maximum deviation.

When the grain geometry is not yet defined and λ_z is unavailable, a simplified expression can be used to estimate the peak chamber pressure based on material characteristics and environmental conditions:

$$P_k^{max} = P_k^{nom} \cdot \frac{0.0044 \cdot \alpha_t \cdot \Delta \mathrm{T} + 1.1}{\sqrt{1-\upsilon}}\,. \quad (5)$$

This formula enables designers to assess pressure risk early in the conceptual design process using only propellant data and environmental temperature deviation.

Erosion and Throat Regression Models

Throat erosion is a critical factor affecting chamber pressure and burn stability, especially in motors using carbon-carbon throat inserts. A dedicated empirical model calculates erosion (Δd_t) as a function of time, propellant gas aggressiveness, and throat material density:

$$\Delta d_t = k_1 \cdot k_2 \frac{P_k^{n1} \cdot P_k^{n2} \cdot \varphi \cdot \tau}{\rho}\,, \quad (6)$$

where τ – burn time, s; φ – oxidizer potential, dimensionless; ρ – insert material density, $kg \cdot m^3$; P_k – chamber pressure and temperature, Pa. This model helps assess nozzle throat durability and stability during long-duration burns.

Structural Mass and Component Weight Models

Mass estimation models are tailored to the specific geometric and structural characteristics of SRM components. While basic formulas rely on volume and material density, correction factors are introduced for: mounting interfaces (e.g., flanges, bulkhead fittings); launch system integration structures; reinforced sections subject to high stress. For example, mass estimates for forward hatches or nozzle mounting rings are adjusted based on empirical deviations observed during manufacturing (AbdelGawad & Guozhu, 2022).

Statistical Calibration and Validation

All models are calibrated using legacy datasets derived from the design and testing of real SRMs. The comparison of predicted versus actual parameters showed deviation ranges of structural mass from – 1.8% to + 3%; specific impulse from – 0.15% to – 0.3%; overall motor length from – 1.8% to + 3.2%.

These margins confirm that the analytical models, when properly calibrated, can provide reliable approximations suitable for the preliminary design phase.

Algorithmic Implementation and Calculation Workflow

The proposed methodology has been implemented as a structured calculation tool that enables rapid evaluation of various SRM configurations on a standard personal computer. The core objective of the implementation is to provide engineers with a fast, flexible, and user-friendly system that facilitates early-stage decision-making without compromising accuracy.

Software Platform and Tools

The methodology was originally implemented using Microsoft Excel combined with custom macros and formula libraries. This environment was selected for its accessibility, ease of use, and support for parametric tabulation, graphical analysis, and modular design logic. The tool can be extended or ported to more advanced platforms (e.g., Python or MATLAB) if integration with external simulation packages is needed.

Input Interface

Users begin by entering or selecting required mission parameters (e.g., payload mass, flight duration); initial geometric constraints (motor length, diameter limits); ranges for design variables (pressure, burn time, expansion ratio); optimization criteria (e.g., mass minimization, performance maximization). The interface also includes default material properties, propellant characteristics, and empirical correction coefficients, which can be adjusted if custom data is available.

Calculation Logic and Workflow

The computational core proceeds through the following steps. (1) Initialization: Set up design space grid based on variable ranges. (2) Geometry Estimation: Calculate internal motor volume, charge shape factor, nozzle dimensions. (3) Internal Ballistic Simulation: Estimate chamber pressure, propellant mass flow rate, burn duration, and thrust profile. (4) Thermodynamic Analysis: Compute specific impulse, temperature, and exhaust parameters. (5) Structural Assessment: Estimate motor casing mass, thermal loads, and stress factors. (6) Erosion Model: Apply throat regression model to check nozzle stability. (7) Feasibility Check: Evaluate constraint violations (e.g., overstress, integration limits). (8) Result Compilation: Store all outputs for analysis and ranking. Each configuration is processed automatically, and results are stored in tabular form for batch comparison.

Output Visualization

The system includes basic visualization tools to plot thrust vs. time profiles; compare mass and performance trade-offs across design variants; highlight constraint-violating configurations; generate summary charts for engineering reports or presentations.

Performance

On a typical desktop system, the tool can evaluate hundreds of configurations in minutes. This enables fast iteration and supports design optimization loops without requiring high-performance computing resources.

The Mathematical model of an SRM

An SRM mathematical model is an abstract, formally defined representation suitable for analysis via mathematical methods and simulation. It replaces the real engine and its behavior with a collection of elementary subprocesses of different physical character. During design, emphasis is placed on processes that affect flight conditions, thrust output, propellant consumption, mass and energy balances, performance efficiency, and related parameters (Senkin & Syutkina-Doronina, 2019).

To formulate the model mathematically, we adopt a block-based approach in which each block encapsulates a set of equations describing an elementary subprocess within the system. The SRM design model is composed of the following blocks: geometrical block; mass block; ballistic block; energy block; structural (strength) block.

Individual equation groups are assembled into a single system that constitutes the mathematical description of the SRM (Oglykh et al., 2010). This mathematical model is then translated into specialized algorithms for computer simulation of the engine's operational processes. The model and associated simulation algorithms form the basis for methodological and software instruments used in optimization at early design stages and for determining the SRM's principal characteristics. The complete SRM mathematical model, built according to a block-based methodology, includes the following components: block for determining the energy characteristics of the SRM; block for determining the dimensional (geometrical) characteristics of the SRM; block for determining the mass characteristics of the SRM. Figure 2 shows a schematic diagram of the SRM mathematical model.

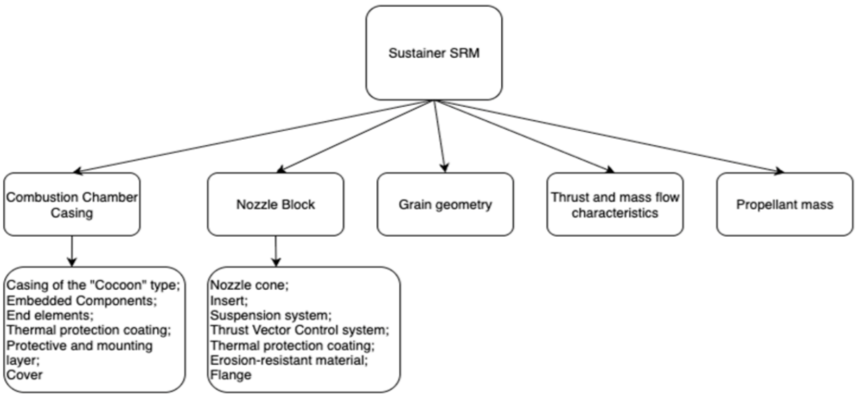

Figure 2 – Schematic diagram of the SRM mathematical model (Source: Authors)

As an illustrative example, this section presents a mathematical model describing the dimensional and mass characteristics of the SRM. The dimensional and mass characteristics of the solid-propellant tactical missile (SPTM) encompass the overall dimensions and mass properties of the motor itself, as well as its principal subsystems and components. These characteristics are determined from the values of key design parameters, input data, and the SRM's structural-layout configuration. The SRM of an operational-tactical missile must satisfy the optimal requirements for its structural configuration. To achieve the designated performance objectives, the design must employ lightweight yet durable casing, ensuring a maximal structural mass fraction, defined as:

$$\alpha = \frac{M_{str}}{M_{prop}}, \tag{7}$$

where M_{str} – structural mass, kg; M_{prop} – propellant mass, kg. Additionally, the system must incorporate a nozzle block with thrust vector control components, ensuring the complete execution of the prescribed flight program. The overall length of the SPTM, L_{SPTM}, is calculated using the following relation:

$$L_{SPTM}(\bar{p}, \bar{x}) = L_{WSL} + L_{SRM}(\bar{p}, \bar{x}) + L_{UML} \tag{8}$$

where $\bar{p}$ – vector of SPTM parameters to be optimized; $\bar{x}$ – input data vector; L_{WSL} – length of the warhead section of the SPTM, m; L_{SPRM} – length of the sustainer SRM, m; L_{UML} – unaccounted length of the SPTM, m.

Under constraints on the maximum allowable length and design parameters of the SPTM, the initial mass $m_0(\bar{p}, \bar{x})$ can be determined by solving the following transcendental equation:

$$L_{SPTM}(\bar{p}, \bar{x}, m_0) = L_{SPTM}^{lim}, \tag{9}$$

where L_{SPTM}^{lim} – limit on the total length of the SPTM, m.

The payload mass, m_{pl}, is defined as the total mass of the warhead section, encompassing the mass properties of all constituent elements and subsystems. It is assumed that m_{pl} includes the mass of the SPTM flight control system instrumentation, as well as the complete set of countermeasures for missile defense penetration. Taking these factors into account, the mass of the warhead section, m_{pl}, can be determined using the following relation:

$$m_{pl} = m_0 - \lfloor m_{SPRM}(\bar{p}, \bar{x}) + m_{IS}(\bar{p}, \bar{x}) + m_{TS}(\bar{p}, \bar{x}) + m_u \rfloor \tag{10}$$

where m_{IS}, m_{TS} – masses of the transition and tail sections, kg; m_{SPRM} – mass of the sustainer SPRM, kg; m_u – unaccounted masses of elements and subsystems, whose calculations are not performed within the algorithm for determining the main characteristics of the SPTM, kg (Sforzini, 1972).

The masses of the transition and tail sections are determined by the following relations

$$m_{IS} = \pi \cdot \rho_{md} \cdot L_{IS} \cdot \delta_{eqt} \cdot (2 \cdot R_{ex} - \delta_{eqt}) \tag{11}$$

$$m_{TS} = \pi \cdot \rho_{md} \cdot L_{TS} \cdot \delta_{eqt} \cdot (2 \cdot R_{ex} - \delta_{eqt}) \tag{12}$$

where ρ_{md} – density of the material used for manufacturing the sections, $kg \cdot m^3$; L_{IS}, L_{TS} – lengths of the transition and tail sections, respectively, m; R_{ex} – external radius of the cylindrical part of the SPRM combustion chamber, m; δ_{eqt} – equivalent thickness of the nominally smooth shell of the sections, m.

For axial compressive loading, the equivalent thickness of a nominally smooth shell produced by chemical etching is determined by the following relation:

$$\delta_{eqt} = 1.78 \cdot \sqrt{\frac{F_{AxC}}{2 \cdot \pi \cdot K_{st} \cdot E \cdot (\psi + 0.2)}} \tag{13}$$

where K_{st} – stability coefficient under axial compressive loading, dimensionless. $K_{st} = 0.28 \div 0.34$; E – Young's modulus of elasticity, Pa(N·m^{-2}); ψ – reinforcement efficiency factor, dimensionless; F_{AxC} – axial compressive force, N.

If the shell is manufactured by mechanical milling, the equivalent thickness δ_{eqt} is determined by the following relation:

$$\delta_{eqt} = 1.48 \cdot \sqrt{\frac{F_{AxC}}{2 \cdot \pi \cdot K_{st} \cdot E \cdot (\psi - 0.25)}} \tag{14}$$

The reinforcement efficiency factor ψ, in the case when the primary load is axial compression and the shell is manufactured by chemical etching, is determined by the following relation:

$$\psi = 14.4 \cdot \frac{(R_{ex} \cdot \sigma_t)^2}{K_{st} \cdot E \cdot F_{AxC}} \tag{15}$$

where σ_t – ultimate strength of the material used for manufacturing the sections, Pa(N·m^{-2}). If the shell is manufactured by mechanical milling, the reinforcement efficiency factor ψ is determined by the following relation:

$$\psi = 9.9 \cdot \frac{(R_{ex} \cdot \sigma_t)^2}{K_{st} \cdot E \cdot F_{AxC}} \tag{16}$$

The calculated value of the axial compressive force F_{AxC} is determined by the following relation:

$$F_{AxC} = \gamma \cdot F \tag{17}$$

where F – operational compressive force acting on the section, N; γ – safety factor, dimensionless. The length of the tail section L_{TS} is determined by the following relation

$$L_{TS} = h_{RH} - L_{NB} \cdot \frac{1-\eta}{1+n_{fn}} - L_{rec} \tag{18}$$

where h_{RH} – height of the rear dome of the sustainer SRM combustion chamber, m; L_{NB} – length of the engine nozzle block, m; η – degree of nozzle block embedding into the combustion chamber, dimensionless; n_{fn} – number of folds in the nozzle part not embedded in the combustion chamber, dimensionless; L_{rec} – length of the part of the rear end component not contacting the combustion chamber casing, m (Oyedeko & Egwenu, 2021).

Advantages and Limitations

The automated evaluation methodology for SRMs offers significant benefits for early-stage missile system design. At the same time, its application scope is defined by the assumptions, simplifications, and data sources embedded in the model (Hashish, 2018). This section outlines both the strengths and constraints of the approach.

Advantages

1. *Rapid Evaluation of Multiple Configurations*. The methodology enables engineers to analyze dozens or even hundreds of

SRM design variants in a matter of minutes. This significantly accelerates trade-off studies and supports agile decision-making during concept selection.

2. *Reduced Dependence on Specialized Experts*. By incorporating essential calculation models and calibrated empirical data, the system allows a single engineer to conduct comprehensive assessments without relying on multiple domain specialists in ballistics, thermodynamics, or structural mechanics.

3. *Built-In Optimization and Constraint Handling*. The methodology supports the definition of performance criteria (e.g., range, efficiency, structural mass) and geometric or operational constraints. Infeasible solutions are automatically filtered out, ensuring the practicality of design options.

4. *Adaptability Across Missile Classes*. The modular design of the tool allows its application to various classes of rockets – from short-range tactical systems to ICBMs and launch vehicles – by simply adjusting input parameter ranges and performance targets.

5. *Statistically Calibrated Accuracy*. Thanks to reliance on real-world development data, the methodology offers a validated level of precision sufficient for the early stages of design, where rough yet trustworthy estimates are more valuable than detailed simulations.

Calculation Logic and Workflow

1. *Not Suitable for Final Design Verification*. The tool does not replace detailed 3D modeling, CFD, or FEA simulations. It is not intended for final validation of thermal or structural loads or for generating detailed manufacturing documentation.

2. *Limited to Typical SRM Architectures*. The methodology assumes common motor structures, such as bonded charges, single-chamber configurations, and standard nozzle geometries. Unconventional or experimental designs may fall outside its scope of validity (Ellis & Keller, 1975).

3. *Empirical Dependency on Historical Data*. Accuracy is heavily dependent on statistical data from past development projects. If new materials or production technologies are introduced (e.g., additive manufacturing, novel composites), recalibration may be required.

4. *Simplified Modeling of Transient Phenomena*. The current implementation does not account for certain time-dependent effects such as dynamic pressure spikes, ignition transients, or complex grain burnback patterns, which can be relevant in some mission scenarios.

Despite these limitations, the methodology fills a critical gap in the engineering workflow by offering a practical and validated tool for the early evaluation of SRM concepts – bridging the divide between idea and high-fidelity simulation (Zosimovych, 2021).

Future Directions

The development of the automated evaluation methodology represents an important step toward accelerating the preliminary design of SRMs. However, continued advances in propulsion technologies, materials, and computational tools offer numerous opportunities for expanding and refining the system's capabilities. This section outlines potential future enhancements and research directions (Li et al., 2025).

Integration with Modern Design Environments

To improve usability and facilitate design iteration, the methodology can be integrated with: computer-aided design systems for geometry synchronization; multiphysics solvers for thermal, structural, and fluid interaction simulations; model-based systems engineering platforms for broader system-level optimization. Such integration would allow the tool to transition from a standalone calculator into a component of a complete digital design workflow (Rohini et al., 2022).

Support for Advanced Materials and Manufacturing

Emerging technologies such as additive manufacturing, carbon composite casings, and new high-energy propellants require updated modeling approaches. Future versions of the methodology could: include new material property databases; account for hybrid grain geometries; model manufacturing constraints and tolerances. This would enable accurate evaluations of cutting-edge SRM designs that go beyond legacy configurations.

Multi-Objective Optimization and AI Integration

Introducing multi-objective optimization algorithms would allow designers to balance trade-offs between mass, cost, performance, and reliability more effectively (Miller, 1971). Additionally, incorporating machine learning techniques could assist in: predicting optimal parameter combinations based on historical outcomes; reducing computation time for high-dimensional design spaces; identifying non-obvious patterns or failure risks Emerging.

Extension to Multi-Stage Propulsion Systems

While the current methodology is tailored for single-stage SRMs, it could be extended to evaluate multi-stage propulsion stacks by modeling stage separation dynamics; optimizing interstage mass distribution; evaluating stage-specific constraints and sequencing. Such an upgrade would support full mission analysis and increase the relevance of the tool for complete missile and launch vehicle systems (Kamm & Gany, 2008).

Experimental Data Enrichment

To improve accuracy and broaden applicability, future work may focus on: expanding the empirical database with new test results; refining calibration models for specific propellant types and nozzle technologies; validating results across international SRM design programs for generalization. These directions offer a roadmap for transforming the current methodology into a comprehensive and intelligent design assistant, capable of supporting next-generation propulsion development under both traditional and advanced manufacturing paradigms (Terzic et al., 2011).

Conclusion

This paper raises the issue of developing a structured methodology for the automated evaluation of SRMs during the preliminary design phase. Developed on the basis of analytical models and statistical calibration using real-world data from Yuzhnoye State Design Office, the methodology enables engineers to quickly and reliably estimate key motor parameters without the need for detailed simulations or cross-disciplinary coordination.

The system supports a wide range of input parameters and performance criteria, making it applicable to various classes of missile systems – from tactical to intercontinental (Mishra et al., 2022). It provides a fast and efficient tool for evaluating thrust performance, internal ballistics, thermal conditions, and structural characteristics within a unified framework. Through algorithmic implementation and optimization logic, it facilitates the comparison of hundreds of design options in a matter of minutes, significantly accelerating early-stage decision-making.

Validation against previously developed motors demonstrates that the methodology delivers accurate predictions within acceptable engineering tolerances. Although not intended for final verification or certification, it serves as a powerful screening and optimization tool, helping to identify promising design directions early in the development cycle (Zhang et al., 2025).

By bridging the gap between conceptual ideas and detailed simulation environments, this methodology fills a critical niche in the missile design workflow. With future enhancements – such as support for advanced materials, integration with CAD systems, and AI-driven optimization – it has the potential to evolve into a comprehensive design assistant for modern propulsion development.

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Laser Micro-Texturing and AI-Driven Optimization for Thermal Management of Photovoltaic Systems

Aswin Karkadakattil

Purpose. Photovoltaic (PV) and other renewable systems suffer efficiency and reliability losses from overheating. This review emphasizes the need for scalable, integrated thermal management solutions. **Design / Method / Approach**. The paper evaluates recent advances in laser-based surface micro-texturing as a promising strategy for thermal regulation. Controlled micro/nano-scale structures enhance heat dissipation, expand surface area, and tune wettability. The study also explores the role of artificial intelligence (AI) in predicting, designing, and optimizing laser-induced textures for simultaneous improvements in thermal, optical, and mechanical durability. **Findings**. Laser-processed surfaces provide multifunctional benefits such as enhanced convective cooling, anti-reflection, and self-cleaning, but most demonstrations remain confined to laboratory scale. AI methods including neural networks, evolutionary algorithms, and reinforcement learning show strong predictive capability and multi-objective optimization potential, offering pathways for industrial adoption. **Theoretical Implications**. The review establishes links between surface morphology, thermo-fluid dynamics, and optical behavior, and shows how AI-enabled digital twins can extend these relationships into predictive, generalized models. It also highlights opportunities for modelling coupled thermo-optical effects and advancing data-driven surface engineering. **Practical Implications**. Integrating laser texturing with AI-driven optimization could embed thermal regulation directly into device structures, reducing reliance on external cooling systems and improving field durability. **Originality / Value**. Unlike prior reviews, this work unites laser surface engineering and AI optimization into a roadmap for renewable energy devices, highlighting digital twins and techno-economic assessment as enablers for scale-up. **Research Limitations / Future Research**. Challenges include scalability, durability under harsh environments, limited AI training datasets, and insufficient lifecycle analyses, requiring cross-disciplinary collaboration. **Article Type**. Review Paper.

Keywords:

laser micro-texturing, renewable energy devices, photovoltaic cooling, thermal management, artificial intelligence, optimization

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Мета. Фотоелектричні (PV) та інші відновлювані енергетичні системи втрачають ефективність і надійність через перегрів. У цьому огляді наголошується на необхідності розробки масштабованих інтегрованих рішень для теплового керування. **Дизайн / Метод / Підхід**. Розглянуто останні досягнення лазерного мікротекстурування поверхонь як перспективного підходу до регулювання тепла. Контрольовані мікро- та наноструктури підвищують відведення тепла, збільшують площу поверхні та впливають на змочуваність. Досліджено також можливості штучного інтелекту (ШІ) для прогнозування, проєктування та оптимізації лазерних текстур з метою одночасного покращення теплових, оптичних і механічних властивостей. **Результати**. Лазерно оброблені поверхні забезпечують конвективне охолодження, анти-відбивання та самоочищення, але переважно демонструються на лабораторному рівні. Методи ШІ, включно з нейромережами, еволюційними алгоритмами та підкріплювальним навчанням, ефективні для прогнозування та багатокритеріальної оптимізації, відкриваючи шляхи для промислового застосування. **Теоретичне значення**. Огляд встановлює зв'язки морфології поверхні з тепло- та гідродинамікою і оптикою, показуючи, як цифрові двійники на основі ШІ перетворюють їх у прогнозовані та узагальнені моделі. Виділено перспективи моделювання взаємопов'язаних термооптичних ефектів і розвитку методів поверхневої інженерії на основі даних. **Практичне значення**. Інтеграція лазерного текстурування з оптимізацією на основі ШІ дозволяє вбудувати терморегуляцію в конструкцію пристроїв, зменшуючи потребу у зовнішньому охолодженні та підвищуючи надійність. **Оригінальність / Цінність**. Робота об'єднує лазерну обробку поверхні та оптимізацію за допомогою ШІ в єдину дорожню карту для пристроїв відновлюваної енергетики, виокремлюючи цифрові двійники та техніко-економічну оцінку як ключові фактори масштабування. **Обмеження дослідження / Майбутні дослідження**. Основні складнощі пов'язані з масштабуванням, довговічністю в жорстких умовах, обмеженістю навчальних наборів даних для ШІ та недостатністю аналізу життєвого циклу, що вимагає міждисциплінарної співпраці. **Тип статті**. Оглядова стаття.

Ключові слова:

лазерне мікротекстурування, пристрої відновлюваної енергетики, охолодження фотоелектричних систем, теплове керування, штучний інтелект, оптимізація

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The accelerating global shift toward renewable energy has firmly positioned photovoltaic (PV) technologies as a cornerstone of sustainable power production. Nevertheless, their operational efficiency remains highly vulnerable to thermal stress. Elevated module temperatures diminish power conversion efficiency, hasten material degradation, and reduce service lifetime. It is well established that each degree Celsius rise beyond the optimal range can lower PV efficiency by approximately 0.4–0.5% illustrating the pressing demand for advanced thermal regulation. Comparable issues are evident in other solar-based devices, such as photovoltaic–thermal (PV/T) hybrids and solar thermal collectors, where inadequate heat dissipation significantly restricts performance reliability and overall energy yield. To overcome these thermal bottlenecks, multiple cooling strategies have been investigated over the past two decades. Passive approaches including heat sinks, natural convection channels, and phase change materials (PCMs) are cost-effective and maintenance-friendly but frequently lack scalability and stable performance under fluctuating weather conditions. Active cooling methods, such as forced air or liquid circulation, provide superior thermal control yet impose additional energy demands, higher costs, and increased system complexity. Hybrid techniques, combining passive and active measures, have shown promise in boosting efficiency; however, challenges related to economic feasibility, system integration, and long-term durability still remain. These constraints underscore the urgent need for innovative, multifunctional, and economically viable cooling strategies for next-generation renewable devices.

The novelty of this review lies in its systematic synthesis of two disruptive frontiers: laser-based micro-texturing and artificial intelligence (AI). Laser surface texturing has recently attracted attention as a transformative solution. By introducing controlled micro- and nano-scale patterns, laser texturing improves heat dissipation through enhanced convective transfer, enlarged surface area, and engineered wettability. Moreover, such surfaces provide multifunctional advantages including anti-reflection, self-cleaning, and dust-repellent properties attributes highly desirable in outdoor energy harvesting systems. However, the true significance of this approach extends beyond these individual benefits; it represents a paradigm shift from add-on cooling components to integrated, multifunctional surface engineering. Despite these benefits, practical implementation of laser-engineered textures in PV and solar thermal devices is still at an early stage, with most evidence limited to laboratory-scale trials rather than industrial deployment. This gap highlights the critical relevance of a complementary innovation: the integration of artificial intelligence (AI). Traditional trial-and-error methods of optimizing surface patterns are resource-intensive and often yield suboptimal outcomes. AI-based models such as artificial neural networks, genetic algorithms, and reinforcement learning enable predictive mapping of the intricate relationships between texture geometry, heat transfer mechanisms, and device efficiency. Through multi-objective optimization, AI offers the capacity to simultaneously maximize thermal performance, mechanical durability, and optical behaviour, potentially accelerating the industrial adoption of laser-engineered solutions. The interdisciplinarity of this convergence is a core theme of this review, bridging materials engineering, thermal science, laser physics, and computational intelligence. The present review aims to provide a comprehensive account of laser-assisted micro-texturing for thermal management in renewable energy systems, with particular emphasis on AI-driven design and optimization strategies. The discussion begins with an overview of laser–material interactions and mechanisms underlying texture formation, followed by an assessment of current applications in PV, PV/T, and solar thermal collectors. Subsequently, the role of AI in predictive modelling and performance enhancement is critically examined. The paper concludes with an exploration of existing challenges, unresolved research questions, and a strategic roadmap to guide future work. By integrating these perspectives, this review highlights the transformative potential of laser — AI synergy in enabling high-efficiency, durable, and sustainable renewable energy technologies.

Objectives and Tasks

The objective of this review is to consolidate and critically examine current research on enhancing the thermal management and durability of photovoltaic (PV) and renewable energy systems through laser-based micro-texturing and artificial intelligence (AI)–driven optimization. To achieve this, the following tasks are addressed:

1. Summarize the fundamental principles of laser micro-texturing and its influence on heat transfer, wettability, and optical properties of energy-harvesting surfaces.
2. Compare reported laboratory-scale demonstrations and modelling studies to highlight correlations between texture morphology, thermal regulation, and device performance.
3. Analyse the role of AI and machine learning in predicting, optimizing, and designing multifunctional textures for improved cooling efficiency, optical absorption, and durability.
4. Identify existing limitations, including scalability, environmental durability, data scarcity, and integration with commercial PV and hybrid systems.
5. Outline future research directions, emphasizing digital twins, adaptive AI algorithms, and techno-economic assessments to enable reliable, scalable, and sustainable deployment of laser AI-enabled renewable devices.

The limitations of existing cooling strategies are summarized in Table 1.

Table 1 – Comparison of conventional cooling approaches for photovoltaic (PV) systems (Source: author)

Cooling Approach	Typical Techniques	Reported Efficiency Gain	Cost & Complexity	Key Limitations
Passive	Heat sinks, natural convection channels, fins, phase change materials (PCMs)	2–5% (heat sinks, fins); 4–7% (PCM-based)	Low to moderate cost; simple design; minimal maintenance	Limited scalability; PCM suffers from leakage and long-term stability issues; effectiveness declines under fluctuating solar loads
Active	Forced air cooling, liquid circulation, water spraying, refrigerant-based loops	5–12% (air/liquid); up to 15% (water spray, evaporative)	Higher cost; requires pumps/fans; added energy consumption	Reduced net energy gain due to parasitic power use; increases system complexity; higher operational and maintenance costs
Hybrid	PCM + heat sinks, liquid + PCM, thermoelectric modules + cooling	8–12% (PCM + heat sink); 10–15% (PCM + liquid); up to 18% (thermoelectric hybrids in prototypes)	Moderate to high; requires integration of multiple components	Integration challenges; increased weight; reliability and durability concerns; cost-effectiveness at large scale remains unproven

Fundamentals of Laser Micro-Texturing

Principles of Laser-Material Interaction

Laser micro-texturing relies on the precise interaction of photons with a solid surface, producing effects such as localized melting, ablation, or photochemical modification. The process is governed by laser wavelength, fluence, and pulse duration, along with the optical-thermal properties of the substrate (Toyserkani & Rasti, 2015; Bonse, Kirner, & Krüger, 2020).

Nanosecond lasers operate primarily in the thermal regime. For instance, Liu et al. (2022) reported that ns pulses produced grooves and dimples on stainless steel, but with heat-affected zones (HAZ) up to 20 μm and frequent microcracking. Their advantage lies in cost-effectiveness and scalability, but precision is limited.

Picosecond lasers partly suppress electron–phonon coupling, enabling cleaner ablation. Wang et al. (2019) demonstrated that ps pulses reduced the HAZ to <1 μm on titanium alloys, yielding smoother ripple patterns and improved uniformity.

Femtosecond lasers deliver ultrafast, non-thermal energy deposition through multiphoton ionization and Coulomb explosion. Vorobyev and Guo (2013) observed ripple periodicities of 400–700 nm on silicon with negligible collateral damage, while Sugioka and Cheng (2014) demonstrated defect-free nanochannels in glass. Such precision makes fs systems especially promising for photovoltaics (PV), where surface quality directly affects optical absorption and long-term durability (Singh & Guo, 2022).

Significance. While ns systems remain attractive for large-area, low-cost processing, ps and fs lasers offer the precision and reliability essential for PV and semiconductor devices.

Mechanisms of Micro/Nano-Texture Formation

Different physical pathways contribute to texture development.

Laser-induced periodic surface structures (LIPSS). Arise from interference between incident and scattered light. Bonse et al. (2020) demonstrated sub-wavelength ripples (~500 nm spacing) that improve anti-reflective properties of metallic surfaces.

Capillary flow and resolidification. Molten material can reflow and freeze into grooves or ridges. Sierra, Edwardson, and Dearden (2018) generated ~10 µm channels on titanium, improving surface wettability.

Micro-explosions and plasma expansion. At fluences above ~1 J/cm², rapid vaporization produces craters or pits. Such features enhance nucleation sites for boiling and improve heat transfer efficiency (Toyserkani & Rasti, 2015).

Photochemical modification. Particularly relevant in polymers. Obilor et al. (2022) showed that fs-laser texturing alters polymer chemistry, enabling transitions between hydrophilic and hydrophobic states for tailored self-cleaning behavior.

Significance. These mechanisms can be selectively activated through parameter tuning, offering application-specific benefits such as improved cooling, light trapping, or dust repellence in PV devices (Andueza et al., 2021).

Key Processing Parameters

Surface features are highly sensitive to laser parameters and their interplay.

Fluence. Defines whether energy is below the ablation threshold (surface modification) or above (material removal). For silicon, fs ablation begins at ~0.2 J/cm², while ns systems require ~1 J/cm² (Vorobyev & Guo, 2013).

Wavelength. Shorter UV wavelengths penetrate less deeply, enabling high-resolution structuring of polymers and semiconductors (Wang & Wang, 2022).

Pulse duration. fs–ps pulses minimize heat diffusion. Sugioka and Cheng (2014) observed that fs pulses produced nanochannels free of thermal defects, while ns pulses caused micrometer-scale HAZ.

Repetition rate. Enhances throughput but risks cumulative heating. Kalinowski et al. (2023) reported that >500 kHz repetition rates in ps lasers led to local remelting.

Scan speed and hatch distance. Govern pulse overlap. Joe et al. (2017) demonstrated tunable micro-patterns in polymers by optimizing scanning strategies.

Processing atmosphere. Inert gas environments suppress oxidation and plasma shielding. Yilbas et al. (2018) showed improved finish on Inconel 718 surfaces when processed in argon compared to air.

Significance. For PV devices, fs–ps pulses at optimized fluence and repetition rates offer a balance between precision, processing speed, and industrial scalability.

Types of Laser-Induced Surface Textures

Laser micro-texturing enables a wide range of functional morphologies:

Grooves and channels. Promote liquid spreading and enhance convective cooling (Vorobyev & Guo, 2013).

Dimples and pits. Serve as nucleation sites for phase-change cooling, reducing thermal resistance (Liu et al., 2022).

Hierarchical micro/nanostructures. Replicate lotus-leaf topographies, achieving hydrophobicity and dust repellence (Guo, Zhang, & Hu, 2022).

LIPSS. Sub-wavelength ripples that improve light absorption and reduce reflectance in PV devices (Bonse et al., 2020; Andueza et al., 2021).

Significance. These multifunctional textures allow surfaces to simultaneously improve thermal management, optical efficiency, and durability key requirements for next-generation renewable energy systems. The different pulse-regime mechanisms are summarized in Figure 1.

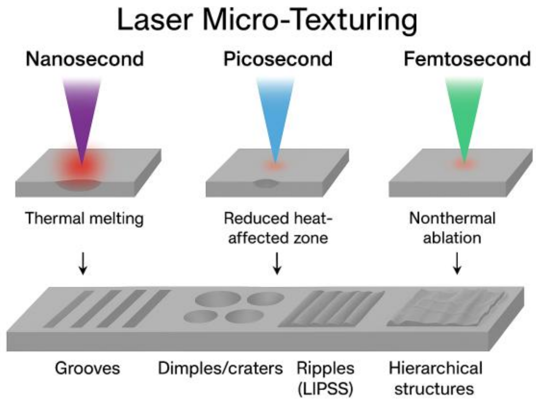

Figure 1 – Schematic of laser micro-texturing across pulse regimes (Authors own elaboration)

Nanosecond pulses induce melting and resolidification, forming dimples and grooves. Picosecond pulses minimize heat-affected zones for controlled ablation, while femtosecond pulses enable ultrafast non-thermal ablation and LIPSS, creating hierarchical micro/nano-textures. Surface morphology depends on fluence, wavelength, pulse duration, and scan speed. As summarized in Table 2, different material classes require tailored laser parameters to achieve desired functionalities.

Table 2 – Typical laser parameters used for micro-texturing of different materials (Source: author)

Material Type	Common Laser Sources	Pulse Duration	Wavelength Range, nm	Fluence Range, J/cm²	Representative Surface Features	Relevant Applications
Metals (Al, Cu, Ti, Stainless Steel)	Fiber (Yb), Nd: YAG, Femtosecond Ti: Sapphire	ns–fs	355–1064	0.2–5.0	Grooves, dimples, LIPSS, hierarchical micro/nano patterns	Heat transfer enhancement, anti-fouling, biomedical coatings
Semiconductors (Si, GaAs)	Femtosecond Ti: Sapphire, Excimer (KrF, ArF)	fs–ps	193–800	0.1–1.0	Nano-ripples, micro holes, super hydrophilic textures	PV anti-reflection layers, enhanced light trapping
Polymers (PMMA, PET, PDMS)	Excimer, CO_2, Femtosecond Fiber	ns–fs	193–10600	0.05–0.5	Smooth ablation zones, microchannels, hierarchical patterns, chemical modifications	Microfluidics, wettability tuning, optical films
Ceramics & Composites (ZrO_2, Al_2O_3, SiC)	Femtosecond Fiber, CO_2, Nd: YAG	fs–ns	532–10600	0.2–2.0	Nano-porous surfaces, microchannels, controlled cracks	Thermal barrier coatings, structural components, optical devices

Applications of Laser Micro-Texturing in Renewable Energy Devices

Photovoltaic Panels

Photovoltaic (PV) modules are constrained by two persistent challenges: optical reflection losses, which prevent full utilization of incident solar radiation, and thermal accumulation, which accelerates material degradation and lowers conversion efficiency (Joo et al., 2023; Khan et al., 2025). Addressing both simultaneously is essential for long-term, high-efficiency solar power generation.

Laser micro-texturing has emerged as a multifunctional solution to these problems. By fabricating sub-wavelength ripples and hierarchical surface patterns, textured layers suppress broadband reflection, thereby enhancing light absorption without the need for external coatings (Bonse, Kirner, & Krüger, 2020; Andueza et al., 2021). This optical tailoring translates directly into higher electrical output under real operating conditions.

Beyond optical control, engineered surface morphologies influence heat and contamination behavior. Increasing the effective surface area enhances convective heat transfer, while wettability modification enables self-cleaning functionalities. For instance, hydrophobic and superhydrophobic laser-textured surfaces minimize dust deposition and facilitate rain-assisted removal, a critical advantage for large-scale solar farms operating in dusty or humid environments (Guo, Zhang, & Hu, 2022; Fillion, Riahi, & Edrisy, 2014). Conversely, hydrophilic regions can promote thin water films that boost evaporative cooling under high irradiation.

Experimental studies validate these benefits. Nižetić et al. (2021) and Xu et al. (2021) reported 3–7% improvements in power conversion efficiency when PV modules were integrated with laser-textured layers, with even greater potential when combined with hybrid cooling approaches such as phase-change materials.

As illustrated in Figure 2 (Author's own elaboration), laser-textured PV surfaces deliver a triple benefit: reduced optical reflection, enhanced heat dissipation, and improved self-cleaning. Together, these effects provide an integrated strategy to overcome multiple bottlenecks that limit the performance and durability of current PV technologies.

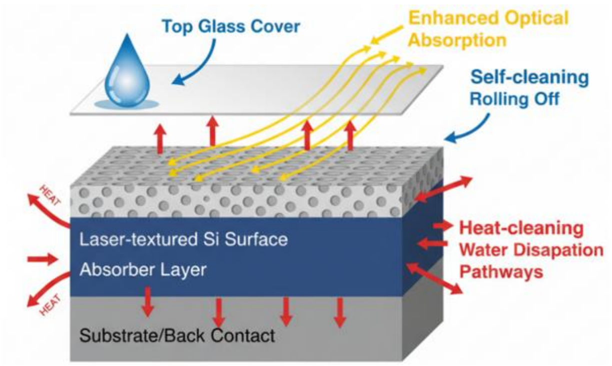

Figure 2 – Schematic of a laser-textured PV cell showing reduced reflectance, enhanced cooling, and self-cleaning for improved performance (Author's elaboration)

Solar Thermal Collectors

In solar thermal systems, the absorber plate is the primary component responsible for harvesting incident radiation and transferring heat to the working fluid. Conventional flat absorbers, however, often suffer from low wettability and modest heat transfer coefficients, particularly under fluctuating thermal loads (Gupta & Tiwari, 2016; Al-Shamkhee et al., 2022). These limitations reduce overall system efficiency and contribute to long-term performance degradation.

Laser micro-texturing has emerged as a promising strategy to overcome these drawbacks. By introducing grooves, dimples, and hierarchical features, laser-modified surfaces promote stronger fluid–surface interactions and enlarge the effective heat transfer area. Such engineered topographies enhance convective heat transfer while simultaneously reducing fouling and scaling tendencies, thereby improving both efficiency and durability (Toyserkani & Rasti, 2015; Liu et al., 2022). Experimental studies support these advantages. For example, nanosecond-laser-fabricated micro-dimpled copper absorber plates have shown up to an 18% increase in heat transfer efficiency compared with untreated surfaces, attributed to turbulence intensification and improved wettability (Sierra, Edwardson, & Dearden, 2018; Wang & Wang, 2022). Similar enhancements have been reported for micro-grooved and ripple-textured absorbers, which provide capillary-driven liquid spreading and localized boiling sites (Bonse, Kirner, & Krüger, 2020). Practical significance: These improvements directly contribute to higher thermal yields in both concentrating solar power (CSP) systems and low-temperature solar heating applications, where durability and sustained performance are critical. As solar thermal collectors continue to expand into industrial and residential markets, laser texturing offers a scalable pathway to achieve higher energy output with reduced maintenance demands.

Hybrid Energy Systems

Hybrid solar technologies, which integrate multiple energy-harvesting functions into a single platform, are increasingly recognized as a pathway toward higher efficiency and resource utilization. Among these, photovoltaic–thermal (PV/T) collectors and solar-assisted desalination units have gained particular attention. Both stands to benefit substantially from the multifunctional properties imparted by laser micro-textured surfaces.

In PV/T collectors, laser-structured absorber plates and heat exchangers facilitate enhanced thermal removal while maintaining electrical performance by regulating module temperature. Xu et al. (2021) demonstrated that coupling PV/T systems with advanced thermal regulation strategies such as phase-change materials can significantly improve energy conversion. Incorporating micro- and nano-textures further strengthens this effect by simultaneously boosting convective heat transfer and reducing surface reflection losses (Andueza et al., 2021; Bonse, Kirner, & Krüger, 2020). Preliminary reports suggest that PV/T units with textured absorbers can achieve 10–15% higher combined efficiency compared to conventional flat-plate designs (Nižetić et al., 2021).

Beyond PV/T systems, solar desalination devices also benefit from laser-enabled surface engineering. Wettability-controlled microtextures accelerate evaporation and mitigate salt scaling, two of the primary bottlenecks in long-term operation (Liang et al., 2023; Chen et al., 2022). For example, picosecond-laser-textured aluminum surfaces have been shown to enhance photothermal water evaporation while resisting fouling, thereby improving freshwater yield under continuous use.

Practical significance. By embedding heat-transfer enhancement, optical tuning, and scaling resistance into the device architecture, laser micro-texturing provides hybrid solar systems with sustained performance improvements and reduced maintenance requirements. This multifunctional approach broadens the role of solar technologies beyond electricity generation, enabling reliable co-production of power, heat, and clean water. Reported improvements in thermal efficiency based on literature are summarized in Table 3.

Table 3 – Reported improvements in thermal efficiency of renewable energy devices using surface texturing (Source: author based on literature)

Renewable Device	Texturing Strategy	Reported Thermal Efficiency Improvement	Additional Functional Benefits	Remarks
Photovoltaic (PV) Panels	Micro-dimples, grooves on Si surface	6–12% reduction in operating temperature; ~4–7% efficiency gain	Anti-reflection, hydrophobicity	Laboratory-scale demonstrations; scalability remains a challenge
Solar Thermal Collectors	Laser-textured absorber plates	8–15% higher heat transfer coefficient	Enhanced absorptivity, reduced fouling	Effective under fluctuating solar flux conditions
PV/T Hybrid Systems	Hierarchical textures on absorber/heat exchanger	10–18% improvement in combined thermal + electrical output	Dust repellence, wettability control	Integration complexity and cost factors
Solar Desalination Units	Textured evaporation surfaces	12–20% increase in evaporation rate	Enhanced solar absorption, salt-crust mitigation	Promising for off-grid and arid-region applications
Concentrated Solar Systems	Textured metallic receivers	5–10% improved heat absorption efficiency	Improved spectral selectivity	Long-term durability under high flux must be validated

Thermal Management Enhancement via Laser-Induced Surface Structures

Effective thermal regulation is one of the most critical factors influencing the efficiency and long-term durability of renewable energy devices. Overheating not only decreases power conversion efficiency in PV modules but also accelerates material degradation and failure in hybrid systems (Joo et al., 2023; Khan et al., 2025). Traditional cooling strategies whether passive or active often require bulky external components or consume additional energy (Nižetić, Papadopoulos, & Giama, 2017; Alao et al., 2025). In contrast, laser-induced surface texturing embeds thermal management directly into the device architecture by modifying surface geometry, altering fluid–surface interactions, and enabling tailored wettability (Bonse, Kirner, & Krüger, 2020; Liu et al., 2022).

Enhanced Convective Heat Transfer

Laser-generated grooves, dimples, and hierarchical roughness intensify fluid motion at the surface by disrupting the thermal boundary layer. This promotes turbulence in both air and liquid environments, improving convective heat transfer. Studies on textured silicon surfaces have demonstrated up to a 15% increase in local heat transfer coefficients relative to untreated substrates (Andueza et al., 2021; Nižetić et al., 2021). Similar results have been reported for textured metallic absorbers in hybrid PV/T systems, where groove-induced turbulence enhances thermal exchange without sacrificing electrical performance (Xu et al., 2021).

Significance. Embedding such microtextures into PV modules reduces surface temperature, directly slowing efficiency losses linked to heat buildup.

Increased Effective Surface Area

A fundamental advantage of laser texturing is the substantial increase in surface-to-volume ratio. Nanostructures such as laser-induced periodic surface structures (LIPSS) and conical features can nearly double the available heat-dissipating area (Bonse et al., 2020). Expanded interfaces enhance conduction into the working fluid and radiation into the ambient environment. For instance, PV cells coated with laser-fabricated micro-dimples have been shown to operate 3–5 °C cooler, corresponding to a 3–5% gain in power conversion efficiency (Andueza et al., 2021; Nižetić et al., 2021).

Significance. Such passive cooling eliminates the need for external fins or fans, reducing maintenance and energy penalties.

Wettability Control and Phase-Change Heat Transfer

Laser structuring also allows precise tuning of wettability. Hydrophilic surfaces encourage thin-film spreading of water, enhancing evaporative and phase-change cooling, while hydrophobic textures enable droplet roll-off, preventing dust accumulation that often creates thermal hotspots (Guo, Zhang, & Hu, 2022; Fillion, Riahi, & Edrisy, 2014).

This dual-mode wettability control is particularly useful in hybrid devices. For example, in solar desalination systems, hydrophilic laser-textured absorbers accelerate evaporation while simultaneously reducing salt scaling, leading to improved thermal efficiency and freshwater yield (Liang et al., 2023; Chen et al., 2022).

Significance. Wettability engineering provides both cooling enhancement and contamination resistance, extending operational lifetime in harsh outdoor conditions.

Case Studies in Renewable Devices

Applications of laser-induced surface structures have been explored across several renewable energy platforms.

Photovoltaic panels. Micro- and nano-structured silicon layers lower cell operating temperature by up to 10 °C while simultaneously improving light absorption (Andueza et al., 2021).

Solar thermal collectors. Laser-textured copper absorber plates demonstrate higher heat flux transfer and greater stability under fluctuating solar conditions (Sierra, Edwardson, & Dearden, 2018; Wang & Wang, 2022).

Hybrid PV/T systems. Hierarchical grooves at absorber–exchanger interfaces balance thermal removal with electrical stability, extending device lifespan (Xu et al., 2021).

Cooling fins and heat sinks. Laser-textured metallic fins show enhanced convection in both natural and forced flow, supporting integration in compact renewable energy modules (Nižetić et al., 2021).

As summarized in Figure 3 (Author's own elaboration), laser texturing enhances heat dissipation by promoting convective airflow or liquid motion, increasing effective surface area, and enabling targeted wettability control.

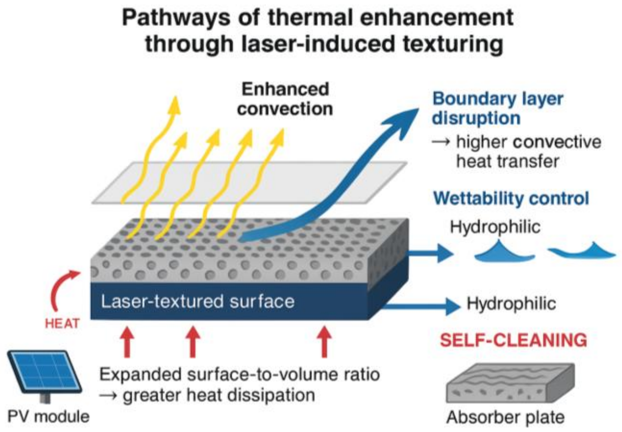

Figure 3 – Thermal management mechanisms of laser-textured surfaces: enhanced convection, higher heat dissipation, and wettability-driven cooling/self-cleaning (Author's elaboration)

Performance comparison between conventional and laser-textured thermal management approaches in photovoltaic systems is shown in Table 4.

Table 4 – Performance comparison between conventional and laser-textured thermal management approaches in photovoltaic systems (Source: author based on literature)

Cooling Strategy	Surface Condition	Typical Temperature Reduction, °C	Relative Efficiency Gain, %	Key Functional Features	Long-Term Stability
Passive Natural Cooling	Smooth absorber surface	2–3	~1–2	Relies solely on ambient convection; limited control	Moderate (degrades with dust/soiling)
Fin-based Cooling	Extruded metal fins	5–7	3–4	Increased surface area; no wettability control	High (mechanically robust, but adds bulk)
Liquid Immersion Cooling	Encapsulated with coolant fluid	8–10	4–6	Direct heat extraction via high thermal capacity fluid	Moderate (risk of leakage, maintenance needed)
Laser-Textured Surface Cooling	Micro/nano-grooved Si surface with tailored wettability	10–15	6–9	Expanded surface-to-volume ratio; induced micro-convection; enhanced evaporative cooling; hydrophobic rolling for self-cleaning	High (surface stability if protected with coating)
Hybrid Laser-Textured + Fins	Textured Si with attached cooling fins	15–18	8–12	Synergistic enhancement of conduction, convection, and evaporation	High (robust under outdoor cycling)

AI-Driven Optimization of Laser Micro-Texturing

The integration of artificial intelligence (AI) with laser surface engineering is transforming the way micro- and nano-scale textures are designed for renewable energy applications. Conventional trial-and-error experimentation is resource-intensive and slow, whereas AI frameworks enable predictive modelling, multi-objective optimization, and adaptive control, significantly reducing experimental overhead while accelerating innovation (Sohrabpoor et al., 2019; Ji et al., 2024).

Role of AI

Different AI paradigms provide complementary strengths.

Artificial neural networks (ANNs). Capture nonlinear relationships between laser parameters (e.g., fluence, pulse duration, scanning speed) and resulting surface features such as groove depth, roughness, or wettability (Sohrabpoor et al., 2019).

Deep learning architectures (CNNs, RNNs). Extract hidden correlations from large process datasets, enabling accurate prediction of texture morphology and energy-related performance outcomes (Sharma et al., 2022).

Evolutionary algorithms (genetic algorithms, particle swarm optimization). Efficiently explore wide parameter spaces and converge on optimal strategies that balance thermal, optical, and mechanical performance (Ji et al., 2024).

Significance. These approaches allow researchers to predict and refine laser processing outcomes before experimentation, saving cost and time while uncovering novel texture designs.

Predictive Modelling

AI frameworks are increasingly used for end-to-end prediction of functional outcomes.

Inputs. Pulse regime, fluence, wavelength, scanning speed, ambient environment.

Outputs. Heat transfer coefficient enhancement, absorptivity gain, self-cleaning potential, durability under thermal cycling.

Validation. Predictions are cross-checked with finite element modelling and experimental techniques such as SEM, AFM, and profilometry (Sohrabpoor et al., 2019; Ji et al., 2024).

Significance. By integrating modelling and experiments, AI ensures predictive reliability, enabling faster scale-up for industrial PV and hybrid systems.

Multi-Objective Optimization

Renewable energy devices demand simultaneous optimization of thermal, optical, and durability-related functions.

Thermal. AI identifies groove and dimple geometries that maximize convective and evaporative cooling (Sharma et al., 2022).

Optical. Models optimize LIPSS periodicity for broadband anti-reflection and light trapping (Bonse et al., 2020).

Durability. Forecasts surface degradation under UV exposure, dust deposition, and humidity cycling (Jordan et al., 2019).

Multi-objective optimization platforms often employ Pareto-front analysis, allowing designers to select parameter sets that achieve balanced trade-offs tailored to specific device requirements (Kenfack et al., 2025).

Cross-Domain Case Studies

Lessons from other engineering domains demonstrate the versatility of AI-guided laser texturing.

Tribology. AI-predicted dimple arrays on bearing surfaces reduce wear, analogous to optimizing micro-textures for thermal transport (Sohrabpoor et al., 2019).

Biomedical devices. ANN-guided femtosecond texturing enhances wettability and osseointegration; similar strategies can be used for hydrophilic coatings in evaporative PV cooling (Sharma et al., 2022).

Aerospace coatings. Deep learning frameworks optimize drag-reducing ablation patterns, showing parallels to optical absorption tuning in PV collectors (Ji et al., 2024).

More directly, AI has already penetrated renewable energy optimization.

PV/T collectors with nanofluids. ML models improved thermal prediction accuracy by >10% over traditional regression (Sharma et al., 2022; Jakhar et al., 2023).

Hybrid ANN–GA approaches. Genetic algorithms tuned neural networks to optimize channel geometries, lowering PV/T operating temperatures by 8–12 °C (Kenfack et al., 2025; Zayed et al., 2023).

Reinforcement learning. Adaptive AI controllers regulate PV output under fluctuating irradiance, reducing parasitic power penalties and improving stability (Xu & Gong, 2023; Kavousi-Fard et al., 2024).

Significance. Embedding AI within laser-assisted surface texturing frameworks enables dual optimization: (i) precise micro-scale texture design, and (ii) system-level thermal management under dynamic operating conditions. This synergy positions AI as a catalyst for scalable, intelligent, and durable renewable energy devices.

Figure 4 illustrates AI-driven loop optimizing laser-textured surfaces for thermal, optical, and durability performance.

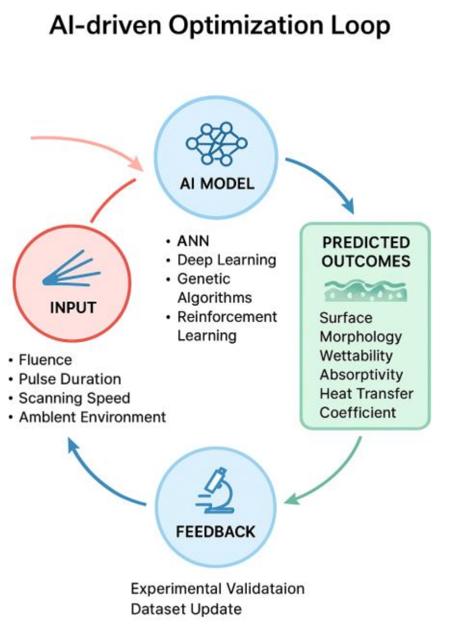

Figure 4 – AI-driven loop optimizing laser-textured surfaces for thermal, optical, and durability performance (Author's elaboration)

Table 5 – AI methods applied in laser texturing and thermal optimization (Source author)

AI Method	Application Scope	Input Dataset	Predicted/Optimized Outcome	Relevance to Renewable Devices
Artificial Neural Networks (ANNs)	Mapping nonlinear process–response	Laser fluence, pulse width, scan speed	Groove depth, surface roughness, wettability state	Prediction of cooling efficiency and optical gain in PV cells
Convolutional Neural Networks (CNNs)	Image-based morphology recognition	SEM/AFM images of textures	Classification of periodic structures (LIPSS, dimples, grooves)	Enables autonomous quality assurance of textured PV/T absorbers
Genetic Algorithms (GA)	Multi-objective optimization	Parameter ranges + constraints	Pareto-optimal solutions for thermal vs. optical trade-offs	Identifies balanced texturing strategies for PV/T collectors
Particle Swarm Optimization (PSO)	Rapid global parameter search	Continuous parameter space	Converges on high-performance settings with fewer iterations	Suitable for real-time adaptive laser control in PV panels
Reinforcement Learning (RL)	Closed-loop adaptive process control	Real-time sensor feedback (temperature, reflectance)	Dynamic adjustment of laser power/speed	Maintains optimal texture under variable solar flux
Hybrid AI–FEM Models	Data-driven + physics-based synergy	FEM simulations + experimental inputs	Predicts heat transfer enhancement and stress resilience	Ensures durability of laser-textured absorbers in outdoor cycling

Challenges and Research Gaps

Although laser-based micro-texturing shows strong potential for improving the thermal management of renewable energy devices, several unresolved challenges continue to limit its translation from laboratory-scale demonstrations to industrial deployment. These challenges span technical, environmental, computational, and economic dimensions, and addressing them is essential to unlock scalable applications. Research gaps and future opportunities for laser-textured renewable energy devices is illustrated in Figure 5.

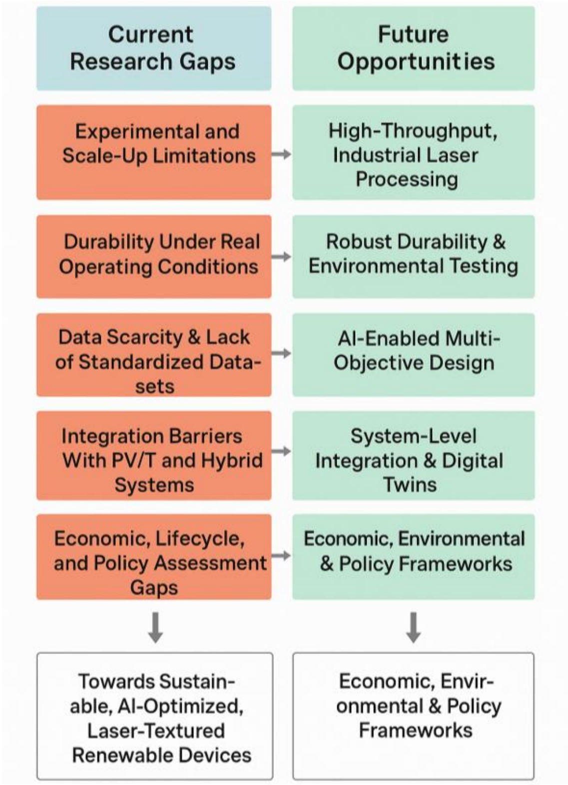

Figure 5 – Research gaps and future opportunities for laser-textured renewable energy devices, highlighting scalability, durability, data, integration, and economic challenges (Author's elaboration)

Experimental and Scale-Up Limitations

Most studies on laser micro-texturing have been performed on small laboratory samples under controlled conditions. Scaling these textures to large-area photovoltaic (PV) modules or solar thermal collectors introduces significant engineering barriers. Current laser systems struggle with high processing times, power consumption, and alignment precision when applied to meter-scale surfaces (Toyserkani & Rasti, 2015; Pfleging, 2020). Achieving uniform micro/nano-features over such areas remains unresolved. Promising directions include high-throughput techniques, such as multi-beam splitting, roll-to-roll laser processing, or hybrid lithography–laser approaches, but these remain at the prototype stage.

Significance. Without breakthroughs in scalability, laser texturing will remain restricted to niche or high-value applications rather than broad PV deployment.

Durability Under Real Operating Environments

Another critical gap is the long-term durability of textured surfaces in harsh outdoor conditions. PV and hybrid systems operate under UV exposure, thermal cycling, humidity, and abrasion from airborne dust. While laboratory experiments confirm enhanced wettability or cooling effects, few studies evaluate stability over years of operation. For example, hydrophilic textures designed for evaporative cooling may degrade through fouling or corrosion, while hydrophobic textures can lose functionality due to abrasion (Conradi et al., 2019; Fillion, Riahi, & Edrisy, 2014). Field studies in desert regions have shown that dust accumulation alone can reduce PV output by 20–30% annually if unmitigated (Kahoul et al., 2014). The interaction of such soiling with textured geometries remains poorly understood.

Significance. Systematic accelerated aging tests and long-term field trials are urgently needed to quantify durability and guide texture designs tailored to real-world environments.

Data Scarcity for AI Model Development

AI frameworks hold strong potential to accelerate laser-texturing design; however, their impact is currently constrained by limited and fragmented datasets. Most reported studies use small, single-laboratory datasets with narrow parameter variation (Sohrabpoor et al., 2019; Sharma et al., 2022). The absence of open-access databases combining laser inputs, material properties, and functional outcomes prevents generalization and cross-validation. Other fields, such as materials genomics and tribology, have shown that collaborative data-sharing platforms can drive rapid progress (Agostinelli et al., 2021).

Significance. Without robust shared datasets, AI models risk overfitting, limiting their ability to reliably guide industrial-scale texture optimization.

Integration with Existing Renewable Energy Systems

The compatibility of textured surfaces with commercial device architectures is another underexplored area. In PV modules, laser processing must avoid damaging encapsulation layers, transparent conductive oxides, or electrical pathways. In hybrid PV/T systems, textures must simultaneously enhance both optical absorption and thermal dissipation without creating trade-offs (Xu et al., 2021; Andueza et al., 2021). Achieving this balance requires holistic design approaches that couple surface engineering with device-level modelling.

Significance. Integration challenges highlight the need for multidisciplinary collaboration across materials science, device engineering, and renewable system design.

Economic and Lifecycle Assessment Gaps

Even if technical performance is improved, the economic viability of laser texturing remains uncertain. High capital costs for fs–ps lasers, coupled with slow processing times per unit area, raise concerns about scalability (Pfleging, 2020). Equally important, lifecycle assessments (LCAs) that account for energy payback, embodied carbon, and long-term maintenance are scarce (Nižetić, Papadopoulos, & Giama, 2017; Hemeida et al., 2022). Without these assessments, the true sustainability benefits of laser texturing cannot be quantified.

Significance. Future work must combine techno-economic analysis with environmental LCA to evaluate whether laser texturing provides net-positive sustainability outcomes at scale.

Future Prospects and Roadmap

The integration of laser-based surface engineering with artificial intelligence (AI) offers a disruptive roadmap for advancing the thermal management and durability of renewable energy systems. However, bridging the gap between laboratory demonstrations and commercial adoption requires a combination of technological, economic, and policy-driven strategies.

Digital Twins for Renewable Devices. The deployment of digital twin frameworks provides a powerful opportunity to replicate and predict the real-time behavior of laser-textured devices. By combining high-fidelity simulations with continuous sensor-driven feedback, digital twins can model degradation pathways, optimize surface properties dynamically, and extend device lifetimes (Xu & Gong, 2023; Kavousi-Fard et al., 2024). Such approaches are particularly relevant for PV and hybrid PV/T systems, where operational conditions fluctuate across climatic zones.

Self-Adaptive AI for Real-Time Optimization. Current AI models often depend on static datasets, limiting their applicability to dynamic field environments. Future progress will depend on reinforcement learning and transfer learning frameworks that allow surface functionalities such as wettability, absorption, and convective cooling capacity to be tuned in real time (Sharma et al., 2022; Ji et al., 2024). This adaptability will be essential for ensuring performance stability in regions with high dust loads, humidity, or temperature swings.

Coupling with Nanofluids, PCMs, and Hybrid Cooling. Laser texturing alone cannot fully overcome thermal bottlenecks. Combining micro-grooved or dimpled surfaces with nanofluids (Mahian et al., 2013; Ghalandari et al., 2020) or phase change materials (PCMs) (Jo et al., 2022; Xu et al., 2021) offers synergistic cooling strategies. Hybrid active–passive configurations, integrating advanced fluids, PCMs, and textured absorbers, could deliver superior thermal buffering and ensure resilience under peak irradiance.

Industrial Scaling and Cost–Benefit Analysis. Scalability remains a major challenge. The next generation of high-throughput laser systems, leveraging beam-shaping optics and multi-beam arrays, will be necessary to texture large-area PV modules cost-effectively (Pfleging, 2020; Coblas et al., 2015). In parallel, techno-economic assessments and lifecycle analyses (Qi et al., 2021; Hemeida et al., 2022) must quantify return on investment, carbon payback, and long-term durability to drive industrial acceptance.

Policy and Sustainability Implications. For laser–AI-enabled devices to gain traction globally, research progress must align with energy policy frameworks. International collaboration is required to set technical standards and certification protocols (Grillo et al., 2024; Van de Kaa & Greeven, 2017). Policy incentives, such as targeted funding for sustainable manufacturing and requirements for lifecycle assessments, will ensure that deployment is not only technologically feasible but also environmentally responsible.

Strategic Outlook. Figure 6 presents a staged roadmap:

Short term (1–3 years). Proof-of-concept validation and open-access dataset development.

Medium term (3–7 years). Industrial pilot systems, techno-economic validation, and digital twin integration.

Long term (7–15 years). Large-scale commercialization, policy harmonization, and global deployment.

Table 6 further outlines research directions with anticipated technical, economic, and environmental impacts, serving as a reference point for academia, industry, and policymakers. Figure 6 illustrates Strategic roadmap for laser-textured renewable energy devices.

Table 6. Suggested research directions and potential impacts for laser-textured renewable energy devices (Source author)

Research Direction	Technical Impact	Economic / Environmental Impact
Digital twin integration for PV and hybrid systems	Enables real-time monitoring, predictive degradation modelling, and adaptive performance optimization.	Reduces maintenance costs; extends device lifetime; lowers lifecycle carbon footprint through predictive fault prevention.
Self-adaptive AI (reinforcement and transfer learning)	Real-time optimization of surface properties (wettability, absorptivity, heat transfer coefficient) under dynamic weather conditions.	Improves energy yield across diverse climates; reduces need for manual reconfiguration; enhances resilience in extreme environments.
Hybrid cooling integration (laser textures + nanofluids/PCMs)	Enhances convective and conductive heat transfer; stabilizes module temperature during peak irradiation.	Cuts energy losses from overheating; improves levelized cost of electricity (LCOE); reduces material wastage by mitigating thermal fatigue.
High-throughput industrial laser systems (beam-shaping, multi-beam arrays)	Scales micro/nano-texturing to industrial PV/T module dimensions; ensures reproducibility and durability.	Reduces per-unit manufacturing cost; accelerates commercialization; enables widespread adoption in utility-scale solar projects.
Lifecycle and techno-economic assessments	Provides rigorous benchmarks for performance, durability, and recyclability under real-world conditions.	Informs investment decisions; ensures compliance with sustainability goals; supports green certification and market competitiveness.
Integration with energy storage and smart grids	Optimizes thermal and electrical balance through coupling with PCMs and AI-driven load management.	Enhances energy security; supports decentralized renewable systems; reduces dependence on fossil backup.
Policy-driven standardization and incentives	Establishes durability, testing, and performance standards for textured renewable devices.	Encourages industry adoption; lowers investment risks; accelerates global deployment with equitable access.

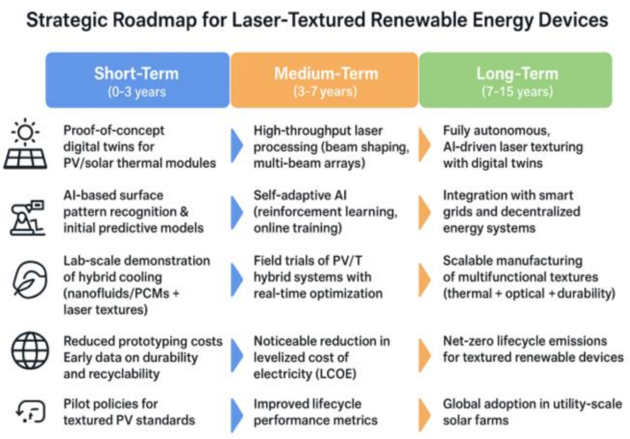

Figure 6 – Strategic roadmap for laser-textured renewable energy devices, outlining short-, medium-, and long-term milestones in technology, economics, and sustainability (Author's elaboration)

Conclusion

This review highlights the emerging paradigm of laser micro-texturing integrated with artificial intelligence (AI) as a disruptive strategy for overcoming thermal management challenges in renewable energy devices. Laser-induced surface structures provide unprecedented control over morphology, wettability, and heat transfer pathways, while AI frameworks enable predictive modelling and multi-objective optimization that extend beyond conventional trial-and-error approaches. Together, these domains pave the way toward scalable, adaptive, and durable cooling solutions capable of enhancing the performance and operational lifespan of photovoltaic (PV), solar thermal, and hybrid energy systems.

Beyond their technical value, these innovations represent an important step in interdisciplinary convergence. Advances in laser–matter interaction, materials science, and thermal engineering must be combined with data-driven approaches such as deep learning, genetic algorithms, and reinforcement learning to fully realize the potential of textured renewable devices. This integration not only improves device-level efficiency but also contributes to broader sustainability goals through reduced lifecycle costs, extended durability, and minimized environmental impact.

Moving forward, progress will require collaborative engagement across multiple domains. Mechanical engineers, materials scientists, and AI researchers must jointly address scale-up barriers, generate standardized open-access datasets, and develop robust digital twins that capture coupled thermal, optical, and environmental dynamics. Equally critical are industry–academia–policy partnerships to ensure that laboratory-scale innovations can be translated into utility-scale deployment.

In conclusion, laser micro-texturing empowered by AI-driven optimization offers a transformative roadmap for renewable energy thermal management. By fostering interdisciplinary collaboration and aligning with sustainability imperatives, this approach holds the potential to accelerate the transition toward high-efficiency, resilient, and environmentally responsible energy systems.

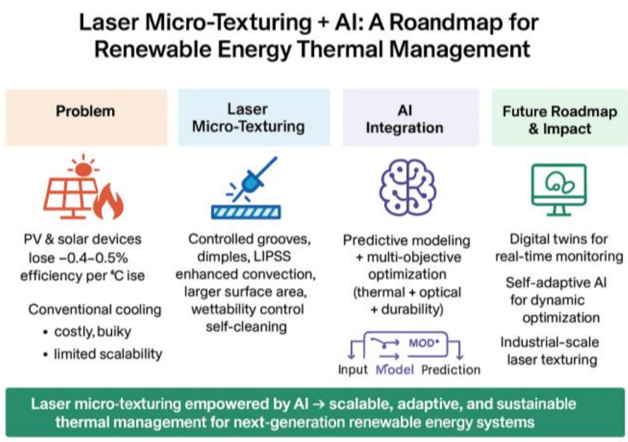

Figure 7 – Graphical summary of laser micro-texturing and AI integration for renewable energy thermal management, highlighting challenges, mechanisms, and future roadmaps (Author's elaboration)

Key Takeaways

– Overheating remains a critical barrier to efficiency and durability in renewable devices, particularly PV systems.

– Conventional cooling methods (passive, active, hybrid) face challenges of cost, durability, and scalability.

– Laser micro-texturing enables controlled surface features that enhance heat dissipation, wettability, and optical absorption.

– Experimental studies report measurable efficiency improvements in PV and solar thermal devices using textured surfaces.

– AI frameworks (ANNs, genetic algorithms, deep learning) accelerate the design and optimization of textured morphologies.

– Cross-sector evidence (tribology, biomedical, aerospace) demonstrates successful integration of surface engineering and AI, offering transferable lessons.

– Major gaps remain, including scalability, environmental durability, dataset availability, and lifecycle assessment.

– Future directions: development of digital twins, real-time adaptive AI, integration with hybrid cooling systems, and policy-supported industrial adoption.

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Managing Innovative Development in International Tourism through Favorable Conditions for Foreign Investment

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Purpose. This study aims to analyze the role of information and communication technologies and innovative investment in managing the development of international tourism. It focuses on identifying tools and approaches that enable enterprises to respond effectively to evolving tourist demands and support sustainable growth. **Findings**. In the tourism industry, where there is a transition from traditional approaches to providing services to personalized ones, the implementation of information technologies allows satisfying the requests of any client as much as possible and with high quality. **Design / Method / Approach**. The article reveals the problem of the need to create and regulate foreign investment in order to manage the development of international tourism using innovations because of scientific and technological progress. **Theoretical Implications**. The accelerated process of restoring global indicators of international tourism after the COVID-19 pandemic is studied and the reasons for the rapid return of the industry to its previous indicators are revealed. Among the reasons, the introduction of modern information and communication technologies and the use of innovative methods of providing services are highlighted. **Practical Implications**. The tools that allow increasing the demand for tourism are analyzed, the main of which are: contactless payment technology, artificial intelligence, virtual and augmented reality, which accelerated the recovery processes. **Originality / Value**. It is proven that in order to transition from the growth paradigm to the sustainable development paradigm in the long term, only sustainable investments in the tourism sector, namely in artificial intelligence and machine learning, will allow increasing the number of tourists and their changing needs. Investments in startups (alternative housing, hotel management and hotel business, artificial intelligence and analytics, aircraft, etc.) cover various participants in distribution technology. **Research Limitations / Future Research.** It is proposed to attract investments for the implementation of innovative projects in tourist regions, which can become an effective tool for economic growth and a guarantee of the country's prosperity. **Article Type**. Analytical.

Keywords:

smart tourism, foreign investment, international tourism, artificial intelligence, sustainable tourism

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Мета. Метою дослідження є аналіз ролі інформаційно-комунікаційних технологій та інноваційних інвестицій у розвитку міжнародного туризму. Акцент зроблено на виявленні інструментів та підходів, що дозволяють підприємствам ефективно реагувати на змінювані потреби туристів і забезпечувати сталий розвиток. **Результати**. В індустрії туризму, де спостерігається перехід від традиційних підходів у наданні послуг до персоналізованих, впровадження інформаційних технологій дозволяє задовольняти запити будь-якого клієнта максимально та якісно. **Дизайн / Метод / Підхід.** Стаття розкриває проблему необхідності створення та регулювання іноземного інвестування з метою управління розвитком міжнародного туризму за рахунок використання інновацій як результату науково-технічного прогресу. **Теоретичне значення.** Досліджено прискорений процес відновлення глобальних показників міжнародного туризму після пандемії COVID-19 та розкрито причини швидкого повернення галузі на колишні показники. Серед причин виділяються впровадження сучасних інформаційно-комунікаційних технологій та використання інноваційних методів надання послуг. **Практичне значення.** Проаналізовано інструменти, що дозволяють збільшувати попит на туризм, основними з яких є: технологія безконтактної оплати, штучний інтелект, віртуальна та доповнена реальність, які прискорили процеси відновлення. **Оригінальність / Цінність**. Доведено, що для переходу від парадигми зростання до парадигми сталого розвитку в довгостроковій перспективі лише стійкі інвестиції в туристичний сектор, а саме в штучний інтелект та машинне навчання, дозволять збільшити кількість туристів та їх потреб, що змінюються. Інвестиції в стартапи (альтернативне житло, управління готелями та готельним бізнесом, штучний інтелект та аналітика, літаки та інше) охоплюють різних учасників технології розповсюдження. **Обмеження дослідження / Майбутні дослідження**. Запропоновано залучення інвестицій для реалізації інноваційних проектів у туристичні регіони, що може стати ефективним інструментом економічного зростання та запорукою процвітання країни. **Тип статті**. Аналітична.

Ключові слова:

смарт-туризм, іноземні інвестиції, міжнародний туризм, штучний інтелект, сталий туризм

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In today's dynamic society, it is important to ensure innovation in all sectors of the economy. In the era of high technology, much attention is paid to innovation and the construction of an innovative world. Tourism is one of the most stable and constantly growing sectors of the global economy, where innovations are a priority for enterprise development, as they attract customers. Innovations and new technologies are an integral part of the competitiveness of tourist enterprises and serve as an effective tool to enhance marketing activities of products and services in the tourism industry.

Tourist enterprises are increasingly involved in the creation of new technologies and the introduction of innovative products for profit. Innovations in tourism are aimed at creating a new product, new approaches to marketing activities, and the use of new management methods using IT technologies.

The theoretical basis of the study is the concept of innovation management, which involves the creation and implementation of new ideas, products, services and technologies in the field of international tourism. Particular attention in the theory is paid to the creation of favorable conditions for foreign investment, which ensures the expansion of infrastructure capabilities, improving the quality of tourism services and stimulating economic growth.

Managing the innovative development of international tourism is now one of the key areas of modern economic policy, as the industry is characterized by high dynamism and multidisciplinary nature (Biletska & Romanchukevych, 2021; Zaytseva et al., 2024). International tourism not only contributes to the development of infrastructure and employment, but also serves as a catalyst for technology transfer and socio-economic innovations (Filiuk, 2022). Innovative development of tourism enterprises requires the integration of new business models, digital solutions and a change in the paradigm of human resource management (Grynko al., 2017; Han, 2024). This transformation is made possible by a combination of public policy, private initiatives and international cooperation, which provides a synergistic effect (Sheviakov et al., 2016; Komarynets et al., 2022). The approach based on the interaction of investment and innovation creates prerequisites for increasing the competitiveness of tourist destinations in the global environment (Sardak & Sarkisian, 2018). A special role in the formation of a favorable innovative environment is played by organizational culture, which determines the ability of tourism and hotel enterprises to implement new technologies and management models (Krupskyi, 2015).

Foreign direct investment is an important mechanism for strengthening the innovative potential of the tourism industry, as it provides access to capital, new technologies and management experience (Kaur, 2019). Studies show that there is a positive relationship between the inflow of foreign capital and the growth of tourist flows, which confirms the multiplier effect of investment on the development of the sector (Antwi, 2022). The example of Japan has demonstrated that international tourism has a positive impact on the total volume of FDI, and not only on the tourism industry, expanding opportunities for technology transfer and regional development (Tomohara, 2016). Similar trends are observed in ASEAN countries, where tourism and FDI complement each other, stimulating economic productivity growth (Rasit et al., 2020). This effect is enhanced under conditions of a stable institutional framework and developed infrastructure, which act as determinants of investment attractiveness (Aida et al., 2023). At the same time, franchising models play an important role in the expansion of the international tourism business, ensuring rapid scalability of services, standardization of quality and integration of innovative solutions into global networks (Krupskyi et al., 2017).

The digitalization of the tourism sector has become a key factor in innovative development, creating the prerequisites for the emergence of "smart" tourist destinations (Sun et al., 2024). Information and communication technologies, artificial intelligence, service automation and service personalization are radically changing the interaction between service providers and consumers (Han, 2024). Online booking platforms, integrated hotel business management systems and recommendation systems based on big data have become widespread in global practice (Damnet et al., 2024). These tools increase the efficiency of operations, reduce transaction costs and form new channels of communication with customers (Komarynets et al., 2022). In turn, digital transformation strengthens the role of human capital, requiring the development of digital competencies of personnel and the implementation of innovative HR practices (Han, 2024). A favorable institutional environment and active government policy create a basis for attracting foreign investment in the tourism sector, as confirmed by the examples of Morocco (Almeida-García, 2017) and Kazakhstan (Shayakhmetova et al., 2020). Government support in the form of tax incentives, simplification of permit procedures, as well as the development of public-private partnerships contribute to the implementation of large-scale infrastructure and innovation projects (Taghiyev, 2023). The formation of tourism clusters and priority development zones ensures the integration of local and international resources, strengthening the competitiveness of destinations (Biletska, 2024). In addition, institutional stability and market transparency increase investor confidence, reducing risks and transaction costs (Arteaga-Alcívar, 2024). Thus, a comprehensive approach to government regulation and investment support forms the long-term prerequisites for sustainable growth of the tourism industry (Zaytseva et al., 2024).

Infrastructure investment plays a key role in the development of international tourism, as it ensures the creation of physical, technological and service capacities to receive tourists (Zhao et al., 2025). Research shows that infrastructure investment has a spatial clustering effect and positively affects the economic growth of tourist regions (Zhou et al., 2016). In Chinese practice, combining infrastructure projects with technological innovations promotes the integration of tourist destinations into global value chains (Zhuang et al., 2021). Infrastructure investments cover not only transport and accommodation, but also digital, communication and environmental infrastructure, which enhances the resilience of the sector (Sun et al., 2024). Thus, the combination of traditional and "soft" infrastructure components creates a multiplier effect and forms the basis for innovative tourism development (Komarynets et al., 2022).

Sustainable and regenerative tourism is becoming a priority for governments and businesses as it responds to new societal expectations for environmental responsibility and social inclusion (Khizar et al., 2023). The concept of regenerative tourism involves not only minimizing negative impacts, but also actively improving the state of local ecosystems and communities (Pung et al., 2024). This approach integrates local knowledge, living systems thinking and intersectoral collaboration, creating multidimensional value for destinations (Komarynets et al., 2022). Sustainable tourism development is based on the UN Sustainable Development Goals, which orient the industry towards a balance of economic, social and environmental interests (Khizar et al., 2023). In the future, this allows for institutionalizing approaches that ensure sustainable growth and long-term attractiveness of investments in the tourism sector (Zaytseva et al., 2024).

Along with the prospects for innovative growth, the tourism industry faces a number of barriers – political instability, lack of reliable insurance mechanisms, terrorist threats and migration risks (Shayakhmetova et al., 2020). In these conditions, the role of information and communication technologies, which allow creating "artificial proximity" and managing remote or risky tourist sites, becomes particularly important (Bystrowska et al., 2017). The use of digital tools allows for increased transparency of operations, improved coordination between stakeholders and increased control over the quality of services (Han, 2024). Combined with international security standards, this builds investor confidence and minimizes transaction costs (Komarynets et al., 2022). Overcoming such barriers is a necessary prerequisite for sustainable investment and the expansion of innovative practices in the tourism sector (Antwi, 2022).

On the other hand, successful management of innovative development of international tourism is possible only under conditions of systemic integration of investment, infrastructure, digital and environmental strategies (Zaytseva et al., 2024). The multi-level nature of tourism as an economic system implies coordination of actions between state, private and public institutions (Han, 2024). In the global context, compliance with international standards of sustainable development is of particular importance, which increase the reputational attractiveness of destinations and facilitate access to financial resources (Khizar et al., 2023). The move towards "smart" tourist destinations is accompanied by an increased role of data and analytics, which allows for informed management decisions and increased effectiveness of marketing strategies (Sun et al., 2024). This approach forms a platform for long-term partnership between investors, the state and local communities (Komarynets et al., 2022).

In summary, it can be argued that international tourism is evolving into a complex system where innovation, investment and sustainability are interconnected and mutually reinforcing (Pung et al., 2024). To achieve sustainable competitiveness, it is necessary to form an effective institutional framework that combines state regulation, private initiatives and international cooperation (Almeida-García, 2017). Creating favorable conditions for foreign investment in tourism is becoming not only a tool for economic growth, but also a mechanism for improving the quality of life of the population and building human capital (Zaytseva et al., 2024). In the future, this will contribute to the emergence of new business models, strengthening partnerships and enhancing the role of technology in providing personalized tourism experiences (Han, 2024). Such a comprehensive approach allows integrating innovative development concepts with global challenges and market trends, ensuring the long-term stability of the tourism sector (Khizar et al., 2023).

According to the concepts of innovative development, effective innovation management involves the formation of a holistic system that includes state policy, support for entrepreneurship, the investment climate, and infrastructure. This system creates incentives for attracting foreign investors to the tourism sector, contributing to the transfer of modern technologies and the improvement of service standards. In addition, it is important to apply economic development theories that emphasize the role of investment in innovation for the long-term growth of the tourism sector. In the context of international tourism, the concept of globalization is particularly relevant, as it expands opportunities for foreign investment and interaction between different cultures. Thus, the theoretical basis of the study focuses on integrating innovation theory with concepts of investment attractiveness, which allows the substantiation of the foundations for creating favorable conditions for foreign investment in international tourism.

Methodology

The article addresses the need to create and regulate foreign investment to manage the development of international tourism through innovations driven by scientific and technological progress. Today, the competitiveness of any enterprise depends on multiple factors, among which the ability to implement and utilize the latest information technology developments is particularly important. This is especially true for the tourism industry, which is undergoing a transition from traditional approaches to personalized services, allowing for maximum satisfaction of individual client needs with high quality. The accelerated recovery of global indicators of international tourism after the COVID-19 pandemic is analyzed, and the reasons for the rapid return to pre-pandemic levels are identified. Key factors include the introduction of modern information and communication technologies and the use of innovative service and maintenance methods. Tools that increase tourism demand are examined, with particular focus on contactless payment technology, artificial intelligence, virtual and augmented reality. The implementation of these technologies during the pandemic facilitated accelerated recovery in the post-pandemic period. It is demonstrated that, to transition from a growth paradigm to a sustainable development paradigm in the long term, only sustainable investments in the tourism sector—specifically in artificial intelligence and machine learning—can increase the number of tourists and meet their evolving needs. Investments in startups covering areas such as alternative housing, hotel and hospitality management, artificial intelligence and analytics, tours and events, enterprise management software, payment and connectivity solutions, smart luggage, ride-hailing and car-sharing, electric and autonomous vehicles, as well as aircraft and flight services, involve diverse participants in distribution technology. It is proposed to attract investments for innovative projects in tourist regions, which can serve as an effective tool for economic growth and a foundation for national prosperity.

The study is based on open sources of information, including official WTO reports, reports of leading global market research organizations. In addition, articles from scientific journals are also used. In particular, the following methods were used: bibliographic analysis was used to systematize the views of domestic and foreign scholars and analyze reports of international organizations to determine the theoretical basis and relevance of the problem; analysis method - when considering the theoretical foundations of innovative tourism development and investment policy under the influence of innovative technologies and investments in innovation management; economic and statistical method - when studying the quantitative assessment and dynamics of the recovery of international arrivals, analyzing the structure of investments in innovation, as well as statistical reports to confirm the impact of innovative technologies on customer loyalty and booking; comparative method - when comparing data from international organizations on different countries and regions and the popularity of various tourist applications; graphic method - in visualizing dynamics through figures and tables; systemic approach - in interpreting innovations as part of the state's investment policy and studying tourism as a complex system; induction and generalization - when combining the conclusions of the literature review and statistical data on the growing importance of personalization and digital services based on specific examples to formulate recommendations for attracting investment and substantiating the concept of sustainable development in tourism.

Findings

The UN World Tourism Barometer publishes that in 2024, about 1.4 billion tourists made international travels, that is, the recovery of tourism compared to the pre-pandemic period is 99%: 140 million more than international tourist arrivals, or an increase by 11% compared to 2023. The results are caused by increased demand for tourist services after the pandemic, reliable indicators of leading tourist companies and constant restoration of destinations in Asia and the Pacific. Positive dynamics are expected to remain during 2025 due to the high demand for tourism services, which, in turn, contributes to the socio-economic development of both known and new areas. This situation determines the huge responsibility of the tourism sector for accelerating the transformation in accordance with the CSR (goals of sustainable development) - focusing attention on people and planet, which undoubtedly determines the relevance and need to study the development of tourism, ways and factors of its development and further formation (UNWTO, 2025).

In 2024, the increase in international arrivals in most directions

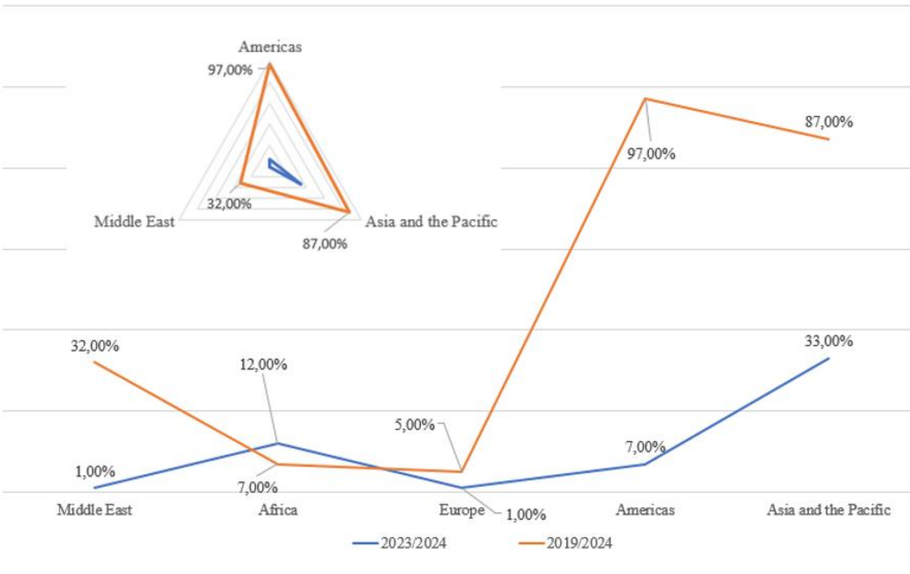

Figure 1 - Dynamics of International Tourism Arrivals by Regions: 2023/2024, 2019/2024. Formed on a basis (UN Tourism, 2025)

was recorded (Fig. 1). The Middle East of the region, where international arrival by 32% exceeded the pandemic level in 2024 and 1% higher than 2023, captures 95 million arrivals. Africa - 74 million arrivals, which is 7% more than in 2019, and 12% more than in 2023. The world's largest destination - Europe reported for 747 million international arrivals in 2024, which is 1% more than in 2019 and 5% compared to 2023. All European subregions have exceeded the level of pandemics, except for Central and Eastern Europe, where many directions are still suffering from Russian aggression against Ukraine.

Two hundred thirteen million international arrivals have been recorded in the US region, which is 97% of pandemics compared to 2019. The Caribbean and Central America countries have already exceeded the 2019 level and compared to 2023 the figure increased by 7%. During 2024, the Asia-Pacific region continued to recover rapidly, and international arrivals increased by 33% in 2024, or by 78 million compared to 2023.

In 2023, the world income of travel applications reached almost $ 1.3 billion, and, according to its forecasts, it will grow steadily over the coming years. Google Maps mobile app, as a traveling app in 2024, was downloaded the most times (Fig. 2) nearly 127 million downloads on iOS and Google Play. Uber's application has become the second largest number of almost 120 million downloads. On the online tourist agencies (OTA) market, Airbnb has headed OTA applications with the largest number of downloads worldwide in 2024, ahead of booking.com.

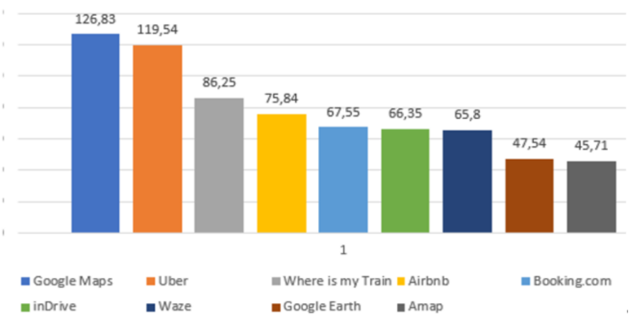

Figure 2 - Market of Appendices of travel agencies online. A total number of loading applications (million times) for travel around the world in 2024. Formed on a basis (Research and Markets, 2025)

In 2023, the global online travel market was estimated at $ 532.1 billion, expected that by 2033 it would reach $ 1876.5 billion from CAGR 13.8% during the predicted period from 2024 to 2033 (Fig. 3).

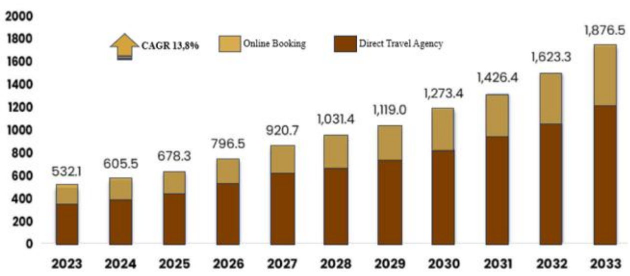

Figure 3 - Global Online Travel Booking Market: forecast 2024-2033. Formed by authors based on (Dzhindzhoyan et al., 2024)

One of the main innovative processes of sales is the use of e - commerce, which can intensively increase the sales of a tourist enterprise on the Internet. The main participants in e-commerce are hotels, airlines, tourist operators and customers. It provides online tours, including global reservation systems (extends beyond the country in which the purchase is made), national reservation systems (within the country) and computer reservation systems (Dzhindzhoyan et al., 2024).

Digital transformation is one of the key priorities of national tourist strategies, as well as strategic emphasis, conditioned by the necessary improvement of efficiency, optimization of functioning, improving productivity, adaptation to the needs of tourists on the way of improving the decision-making process. According to studies conducted from 2018 to April 2024 on investing innovative technologies, artificial intelligence (AI) and machine learning (ML) made almost two -thirds of all agreements for the period under review. Further, the main investment in technology is the Internet of things (IOT) and exciting technologies, which account for 13% and 10% of transactions, respectively.

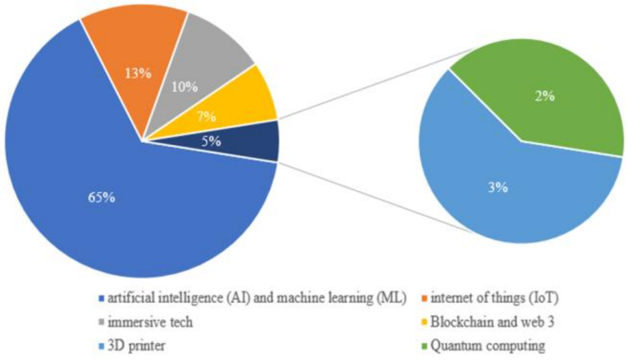

Figure 4 - Distribution of Tech Investment Deals by Travel and Mobility Corporation Worldwide Between 2018 and 2024, by Area of Investment. Formed by the authors based on (UN Tourism, 2024)

According to UNWTO, by 2030 it is expected that the total number of tourist trips will reach 37.4 billion, of which 17.4 billion will be international and domestic overnight (1.8 billion international/15.6 billion domestic). The development contains 2.4 million new hotel rooms worldwide. In addition, the reports mention that the hotel sector consists of almost 200,000 hotels with more than 18 million rooms worldwide. Persistent investments in the tourist sector were directed at «green crossings». The proposal of structures for the transition from the growth paradigm to the paradigm of sustainable development in the long-term perspective involves the development of financial instruments for providing sustainability and renovation of the tourist sector. Therefore, a significant level of investment will be required to support the increased number of travelers and meet their changing needs (Table 1).

Table 1 - Activity Frequency of Foreign Investment Direct

Activity	Frequency of foreign direct investment		
	frequent	occasional	rare
hotels and similar	+		
restaurants and similar	+		
secondary houses	+		
passenger transportation	+		
railway passenger transport services		+	
passenger air transportation		+	
services of road passenger transport			+
water passenger transport services			+
maintenance of passenger transportation			+
travel agencies, etc.			+
cultural service			+
sports and other recreational services			+

Financial FDI data in tourism shows that more than 55% of FDIs come into the construction and development of (material) investments, and about 31% are services and related to platforms (intangible) investments.

Value-added chains in tourism are evolving. From a traditional perspective, products of the tourism subsector include recreational services, accommodation, food services, housing, trade, and construction, among others, which create investment opportunities along the entire value chain. In addition, from a non-traditional perspective, other subsector products arise from capital flows directed toward innovations in travel technology. According to UNWTO investment research, two main groups of subsectors were identified based on raised capital. The first group is associated with mobility-unrelated subsectors, which include alternative housing, hotel management and hospitality, artificial intelligence and analytics, tours and events, enterprise management software, payment and communication solutions, among others (Fig. 5).

In addition, investments in the Travel & Mobility Tech startups have covered several other sub-seats, such as: alternative housing, hotel management and hotel business, artificial intelligence and analytics, tours and events, software for enterprise management, payment and communications, smart and other vehicles. These sub - regions expanded the value creation chain, covering different participants, distribution technologies (Fig. 6).

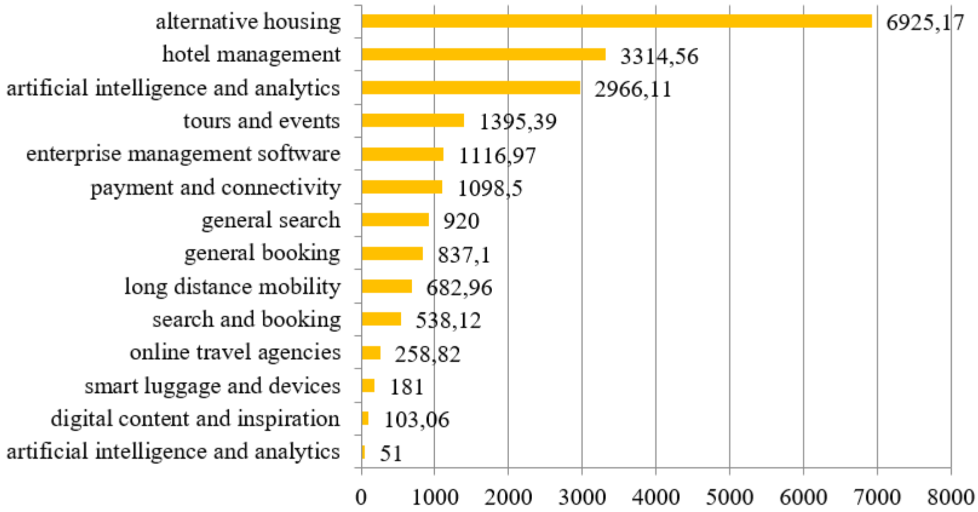

Figure 5 - Funded startups on tourist technologies (not mobile), million dollars. USA

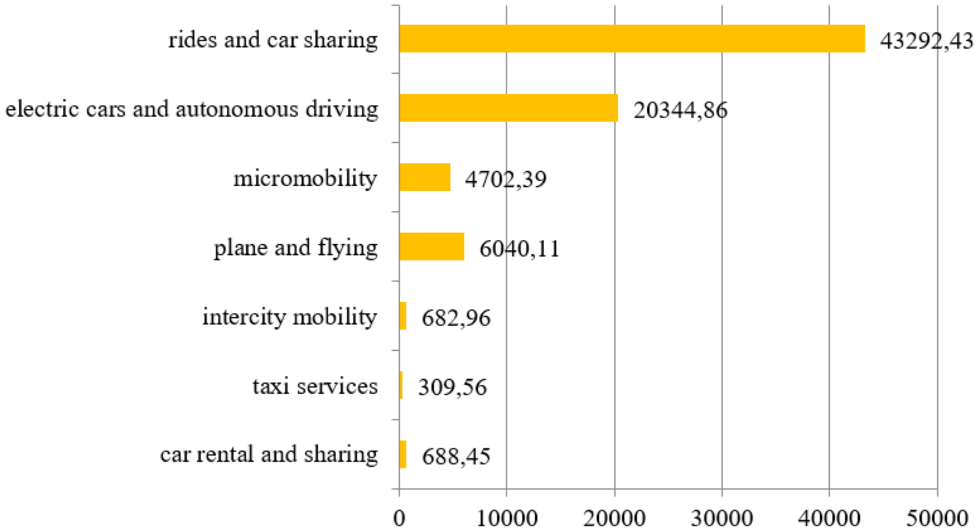

Figure 6 - Sub-sectors tourist technical startups (mobility), million dollars. USA

The results of these two subsector groups are significant in terms of capital accumulation, amounting to approximately $450 billion. Investment in travel technology in the US is notable, but these subsectors are also important for innovation and their interaction with the tourism ecosystem. The integration of the tourism ecosystem and its stakeholders, present in both traditional and non-traditional subsectors, plays a crucial role in enhancing sectoral synergy. Potentially increased demand and developing markets have brought these capital flows to new records. According to MorningStar Equity Research, the booking market is about $ 600 billion. US with an increase of 35.5 to 39.4% by 2029 (Research department Statista, 2025).

Discussion

Looking forward, it is important to understand: the demographic composition of this new market (2030-2040), which will consist mainly of millennials and generation Z. Both are "digital natives", and by 2040 they will be the largest share of the world's population, 3 billion and 2.6 billion respectively. Depending on their socio-economic groups, this behavior may vary significantly. However, the general trend is shifting towards digital and innovative services, especially mobile services. At the same time, there is a shift from traditional to more personalized experiences. In addition, given the consequences of the Covid-19 pandemic, there is a need for the transparency of health, safety, data and safety protocols during travel and final destination. Therefore, a significant level of investment will be required to support the number of travelers and changes in consumer behavior and needs. This can open up several investment opportunities by opening new investment flows from traditional hard investments, such as housing infrastructure, to soft infrastructure, such as digital solutions and support services related to experience and resistance in reality after Covid-19. This new consumer behavior forms tourist markets and is a unique opportunity for implementing innovative solutions. These digital natives require technologies such as 5G, basic cloud services or artificial intelligence. All this offers increased speed of access to information, greater intuition in interaction, the ability to expand tourist experience before and after travel (Research department Statista, 2025).

The complete restoration of international tourism in 2024 was also recorded in other sectoral indicators. First, in 2024, tourism revenues amounted to $ 1.6 trillion, which is about 3% more than in 2023, and 4% more than in 2019. Secondly, according to UN Tourism Tracker, international air bandwidths and air traffic have virtually recovered relatively to pre-pandemic levels by October 2024 (IATA). The global content of the rooms of the accommodation facilities reached 66% in November. According to preliminary estimates, total exports of tourism (including passenger transportation) reached a record $ 1.9 trillion in 2024, which is about 3% more than to the pandemic.

For 2025, trends are designed not only to the positive dynamics of the recovery of the tourism industry, but also to the important tasks: creating a balance between growth and sustainability, introduction of environmental methods of work, meeting the demanding needs of consumers. Practically, each of these steps is related to technology and innovation. After 2019, the requirements, approaches and opportunities for the formation of tourist services have changed, and in particular technologies and innovations help to change the tourism industry and reserve the place of priority business. Technologies and innovations give customers a lot more opportunities and a sense of independence while traveling. For example, a mobile app alone allows you to hunt a large number of different aspects of travel, which shows how important technological innovations in tourism are.

The year of record rates for startups for the tourism industry was 2024. Skift tracked over 200 startups that raised $ 13.1 billion, the total amount of more than twice exceeded 2023, despite the fact that the total number of transactions was approximately the same. Below is an overview of key involvement, financing trends and other important events since 2024 (MySmartJourney, 2025).

Lighthouse fundraising was one of several agreements in 2024, which exceeded all the projects that have been in the tourism industry in recent years. It is a tourist technology company, which rated more than $ 1 billion in 2024. Lighthouse has concluded with the largest venture capital of $ 225 million - a startup of Flyr Aviation Retail. Later, Hostaway raised $ 365 million, which became the largest agreement on short -term real estate management technologies.

The latest report of the Tourism Investment Report 2024, published by Financial Times in collaboration with UN tourism and with the support of Diriyah Gate Company fixes that from 2019 to 2023 investment projects for tourism (1943 projects of direct investment) are collected 259 800 jobs. The European region is a leader in world tourist FDI projects, which involves 867 projects from 2019 to 2023, which is 44.6% of the total volume of world investment, which emphasizes its resistance to cautious investment climate.

Asian-Pacific region: the number of foreign foreign direct investment projects in the region increased by 59.5% between 2022 and 2023 (from 42 to 67), with capital investments increased by 125.3%. During this period, Latin America and the Caribbean attracted 221 FDI tourist projects. This led to investment worth $ 20.5 billion and the creation of approximately 73,400 jobs. As the region has already exceeded the level of arrival of international tourists in 2019, it gives positive confidence of investors in the long -term profitability of the tourist sector of the region.

The Middle East and Africa regions attracted 314 FDI projects in tourism in the total amount of investment of $ 18.1 billion and created about 40,700 jobs. The number of tourists FDIs in the region between 2022 and 2023 increased by 16.1%, from 62 to 72, with capital investments increased by 12.2% (UN Tourism, 2024).

Conclusions

Innovation in the travel and tourism industries can take many forms. In fact, there are a lot of ways in which businesses and corporations keep track of how expensive their customers and tourists are. Obtaining investments for the implementation of innovative projects in the region in the tourism sector can guarantee economic growth and prosperity for the region. Through an innovatively oriented tourism policy, it is possible to achieve greater productivity and stimulate the growth of the economy in the region, achieving the goals of the development of sustainable and inclusive tourism. The basis for investing in innovation in the tourist industry is formed in a complex manner and is the result of the interaction of many levels of management and economic entities. First of all, the key role is played by the power, which through legal regulation, tax policy, investment programs and mechanisms of public-private partnership creates a fundamental institutional and financial foundation for investment activity. Nowadays, outside the authorities (the Ministry of Education, the Ministry of Tourism, the Economy, Innovation, Regional Development) are responsible for the implementation of strategy, distribution of resources, support for start-ups and control over additional investment guarantees. Tourist regions, especially in the spirit of decentralization, often initiate local innovative projects, create tourism clusters, hubs, territories of innovative cooperation and promote Local investor support programs. A significant role is played by subjects of the tourism market - enterprises, associations, start-ups, who are not only recipients of investments, but also initiators of innovation, who formulate the demand for investments new technologies: automated services, smart solutions, blockchain, AR/VR, etc. The development of digital technologies plays a contributing role in stimulating the online market at an even higher rate. Technologies such as mobile additions, artificial intelligence and machine learning, reduce the need for customized support, more expensive and more portable armor, and portable technologies. Accessible via smartphones, and with free access to the Internet, mandrels can be planned and purchased at the right time for the client. It should be noted that such dynamics vary across regions and may lead to singing rhymes. Therefore, effective investment in innovation in tourism is only possible in the minds of the rich mutual relations of the state, the local government, private business and the institutions of the commonwealth - the skins of which plays a structurally identical, but mutually complementary function. The creation of friendly minds for foreign investment in the former regions will lead to increased efficiency in managing the innovative development of international tourism.

The online travel market covers digital platforms and services that simplify travel bookings, including tickets, hotels, car rental and vouchers. This market is developing due to the growth of convenience, the comparison of prices and settings that offer online tools. Key players are travel agencies, meta -searching systems and direct service providers. Technological achievements, such as artificial intelligence-based recommendations and mobile applications, improve users' interaction and accessibility. As the world demand for travel is restored and digital implementation is increasing, the online travel market is ready for significant growth, changing how consumers plan and book their travels. Viewing sales distribution in the world sector of travel and tourism gives a clear idea of a key role, which is played by an online segment that generates about two-thirds of the 2023 market income.

Tourism was one of the first sectors of the economy to use information and communication technologies (ITK) to manage tourist networks and rationalization of operating processes. Airlines have introduced ICT to their information systems and booking systems, launched "global distribution systems", which today allow access to the most favorable offers and prices, immediate booking. Internet technologies have opened new distribution and management opportunities for tourism; it has become one of electronic commerce leading industry.

Consumers of tourist services can book a flight or hotel, download landing coupons in your own phone, buy tickets to the museum, view the restaurant menu with QR code and more. Of course, personal communication and interaction are available to complement the digital experience. However, if visitors want more independence, travel technologies and innovations do it.

NFC technology (close -frequency bond) is a form of wireless technology that allows two devices to "communicate" with each other and exchange data. NFC technology is widely used for contactless payments as well as companies to improve operations and services provided. Like most forms of technology in travel and tourism, NFC technology increases work efficiency and allows to personalize customer experience. One of the leading ways to use NFC technology in hotels is a door key: a physical door key or card, replaces a virtual key that loads clients on their phone and lifts to a digital door panel - it improves safety and efficiency. Hotels also use NFC technology to their interests to facilitate visitors instantly obtaining the information they need and not expect a concierge answer. For example, the MySmartJourney Platform (MySmartJourney, 2025) helps companies to introduce NFC technology in innovative ways to create interesting and unique impressions: broadcasting text, visual, video and 3D content, creating independent excursions to museums, art galleries, historical seats, parks, resorts, etc.

Artificial intelligence (AI) is another form of technology used in the travel and tourism industry. AI is the main way by which tourist businesses accurately and effectively create personalized impressions for their guests. AI can receive and process huge amounts of data, create reports, and keep in touch 24/7. The personalized approach not only improves the booking process but also increases customer loyalty. According to McKinsey, personalization can increase sales by 10-15%, emphasizing the significant potential of profit for platforms that effectively implement the recommendations controlled by AI (McKinsey &Company, 2024).

Virtual reality (VR) is an irreplaceable assistant in the created and demonstration of cruises and tours, which increases the level of booking. Inclusion of virtual reality parameters or augmented reality when viewing numbers, directions or excursions enables guests to see the impressions which they are going to get. During the Covid-19 pandemic, some companies offered excursions with guides on wonderful islands and places so people can enjoy them while staying at home. Digital technologies, including generative artificial intelligence (AI), supplemented with reality (XR) and blockchain, radically change the form of tourism and is a powerful catalyst for innovation in the sector. Travelzoo survey showed that 81% of respondents would be more likely to have a vacation if they were able to feel it practically. The integration of virtual reality into the platform of online travel not only improves interaction with users but also serves as a powerful marketing tool for demonstrating directions and services (World Tourism Alliance, 2023).

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From Awareness to Action: Green Practices in the Iberian Peninsula's Hospitality Sector

Maria Nascimento Cunha

Purpose. This paper examines the adoption of green practices by food and lodging establishments in the Iberian Peninsula's hospitality sector, identifying the extent and character of sustainability integration and revealing structural and behavioural barriers to implementation. **Design / Method / Approach**. A mixed-methods design, emphasising a quantitative survey of employees and customers, was employed, supported by descriptive statistics, independent-sample t-tests, and one-way ANOVA to compare patterns across establishment types, years of operation, and workforce size, enabling robust analysis of environmental practices. **Findings**. Results show strong institutionalisation of waste management, water conservation and sustainable purchasing, alongside consistent but low-cost energy efficiency measures; significant differences emerged between hotels and restaurants, while none appeared by age or size of business; employees displayed high motivation and positive perceptions but limited formal training, and customers reported favourable attitudes yet inconsistent awareness and low willingness to pay a premium. **Theoretical Implications**. The study advances sustainable hospitality literature by demonstrating how micro- and small-enterprises prioritise pragmatic, behaviourally driven measures over capital-intensive innovations, contributing to debates on the attitude–behaviour gap and stakeholder engagement. **Practical Implications**. Findings provide a roadmap for targeted training programmes, communication strategies to enhance customer awareness, and policy interventions to support high-cost investments and sector-specific strategies. **Originality / Value**. This is among the first studies to combine employee and customer perspectives with inferential analysis across multiple sustainability domains in the Iberian Peninsula, producing an empirically grounded picture of green practice adoption at the micro- and small-enterprise level. **Research Limitations / Future Research**. The scope and sample limit generalisability; future work should employ longitudinal designs, develop readiness scales and test interventions to improve customer engagement and willingness to pay. **Article Type**. Applied Research.

Keywords:

sustainable hospitality, green practices, hotels and restaurants, sustainability, environmental management

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Мета. Досліджено впровадження екологічних практик у закладах харчування та розміщення готельно-ресторанного сектору Піренейського півострова з метою визначення масштабів і характеру інтеграції сталого розвитку та виявлення структурних і поведінкових бар'єрів їх реалізації. **Дизайн / Метод / Підхід.** Використано змішаний дизайн із перевагою кількісного анкетування працівників і клієнтів; застосовано описову статистику, t-критерій для незалежних вибірок і однофакторний ANOVA для порівняння практик за типом закладу, роками роботи та чисельністю персоналу. **Результати.** Виявлено високий рівень інституціоналізації управління відходами, збереження води та сталих закупівель разом із послідовними, але маловитратними заходами енергоефективності; зафіксовано суттєві відмінності між готелями та ресторанами, тоді як за віком або розміром бізнесу відмінностей не виявлено; працівники демонструють високу мотивацію та позитивне сприйняття за обмеженої формальної підготовки, а клієнти повідомляють про позитивне ставлення, проте непослідовну обізнаність і низьку готовність сплачувати додатково. **Теоретичне значення.** Показано, що мікро- та малі підприємства віддають перевагу прагматичним поведінковим заходам над капіталомісткими інноваціями, що поглиблює дискусії про розрив між ставленням і поведінкою та залучення стейкхолдерів. **Практичне значення.** Отримані результати пропонують дорожню карту для цільових програм підготовки персоналу, удосконалення комунікаційних стратегій задля підвищення обізнаності клієнтів і політичних інтервенцій для підтримки капіталомістких інвестицій у сталість та секторальних стратегій для готелів і ресторанів. **Оригінальність / Цінність.** Це одне з перших досліджень, що поєднує перспективи працівників і клієнтів із використанням статистичного аналізу кількох сфер сталого розвитку на Піренейському півострові, створюючи емпірично обґрунтовану картину впровадження зелених практик на рівні мікро- та малих підприємств. **Обмеження / Майбутні дослідження.** Невеликий обсяг і вибірка обмежують узагальнення; майбутні дослідження мають застосовувати довготермінові дослідження, шкали готовності та інтервенції для підвищення залучення клієнтів і їхньої готовності платити більше. **Тип статті.** Прикладне дослідження.

Ключові слова:

стала гостинність, екологічні практики, готелі та ресторани, сталий розвиток, екологічний менеджмент

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The global hospitality industry is undergoing a paradigmatic transformation as both businesses and consumers increasingly recognise the necessity of embedding sustainability into core operations to mitigate escalating environmental challenges (Khatter, 2025; Liu et al., 2025). Food and lodging establishments, in particular, are progressively implementing green practices aimed at reducing their ecological footprint while simultaneously improving efficiency and competitiveness (Fraisl et al., 2022). Such initiatives resonate with the broader framework of sustainable development, which seeks to reconcile economic growth with ecological responsibility (Bangura et al., 2024). Within this context, sustainable hospitality encompasses a wide spectrum of practices, ranging from resource conservation, waste reduction, and pollution control to the institutionalisation of eco-friendly policies that actively engage both customers and employees (Moise et al., 2021).

Scholarly literature highlights that the sector's rapid expansion has significantly contributed to environmental degradation, necessitating urgent shifts towards more sustainable business models (Ngoc Khuong et al., 2023). Green practices not only reduce operational costs and environmental damage but also serve as strategic mechanisms for reputation-building and long-term viability (Cunha & Krupskyi, 2023). Nevertheless, evidence suggests that the adoption of environmentally friendly technologies and systemic sustainability initiatives remains uneven across regions and market segments. This disparity is particularly salient in rural hospitality contexts, where structural limitations such as financial constraints, limited human capital, and infrastructural challenges may hinder the uptake of advanced sustainability practices (Abdou et al., 2020; Barakagira & Paapa, 2023; Kusa et al., 2023).

The Iberian Peninsula offers a particularly compelling context for examining these dynamics. Characterised by diverse ecosystems, rich cultural landscapes, and vibrant tourism industries, the region also faces environmental pressures linked to climate change, over-tourism, and resource scarcity (Abellán & García Martínez, 2021; Ahmad et al., 2023; S. C. Pascoal & J. E. Pascoal, 2023). While both Spain and Portugal have committed to ambitious sustainability agendas aligned with the European Green Deal, the practical implementation of sustainability within the hospitality sector remains uneven (Feng et al., 2022; Khan et al., 2022).

Rural areas, in particular, often lack the financial and technological capacity to adopt advanced green practices, despite their reliance on natural and cultural assets that are highly sensitive to ecological degradation (Hariadi et al., 2023; Nguyen Thi Huyen et al., 2025).

Within this landscape, there is a pressing need to evaluate how food and lodging establishments across the Iberian Peninsula integrate sustainability into their operations. This study addresses this gap by systematically examining the extent to which these establishments adopt green practices, assessing their alignment with environmental objectives, and identifying structural or behavioural barriers to implementation (Chornobylskyi et al., 2023; Odeyemi et al., 2024).

By foregrounding the practices and challenges of the hospitality sector in the Iberian Peninsula, this research provides insights of both regional and international significance. For stakeholders, including business owners, policymakers, and local communities, it offers empirical evidence on how sustainability can be operationalised in diverse rural and semi-rural contexts (Anitha Rajathi & Reshma Parveen, 2024). Furthermore, the findings position the Iberian Peninsula as a potential model for balancing economic growth with environmental stewardship, thereby contributing to global discourses on sustainable tourism in ecologically sensitive regions (Satpathy et al., 2022).

Methodology

This study employed a mixed-methods research design, with primary emphasis on quantitative, survey-based inquiry, to systematically examine the adoption of green practices among food and lodging establishments in the Iberian Peninsula. Two key respondent groups were purposively targeted:

(a) employees, including managers, supervisors, and frontline staff, and

(b) customers who regularly patronise these establishments. Data collection was carried out through structured questionnaires developed to assess levels of awareness, perceptions, and engagement with sustainability initiatives.

The surveys were administered over two months, from April to June 2024, using both face-to-face distribution in selected establishments and digital dissemination via online platforms. This dual approach was intended to maximise participation, ensure accessibility, and reduce potential non-response bias (Cunha & Krupskyi, 2023).

For data analysis, descriptive statistics (frequency distributions and percentages) were employed to profile respondents and establish baseline levels of awareness and perceptions. To test for significant differences between independent groups (employees and customers), independent-sample t-tests were applied. In addition, one-way Analysis of Variance (ANOVA) was utilized to compare mean differences across profile variables with more than two categories (e.g., years of operation, business size) (Cunha et al., 2024) ANOVA is a statistical technique that determines whether observed differences between group means are statistically significant, by analyzing the variance within groups against the variance between groups (Marroco, 2021; Esa, & Hashim, 2024). This analytical strategy provided both breadth and depth in identifying patterns of sustainability practices and offered robust insights into how environmental initiatives are being integrated within the regional hospitality sector.

Analysis and Interpretation of Results

Characteristics of the Sample Population

Understanding the characteristics of the sample population is essential to contextualise the findings of this study. By examining the demographic and organisational attributes of participants, this section provides insights into the structure of the hospitality sector in the Iberian Peninsula and highlights factors that may influence the adoption of sustainable practices. Presenting the composition of the sample also enhances the transparency and reliability of the research by allowing readers to assess the representativeness of the data in relation to the broader industry context.

Specifically, this section outlines the distribution of respondents according to type of establishment, years of operation, and workforce size. These variables are particularly relevant, as the literature suggests that enterprise type, longevity, and organisational scale can significantly shape managerial priorities, operational capacities, and willingness to adopt sustainability initiatives. By situating the findings within the demographic and operational profile of the sample, the study ensures a more nuanced interpretation of the results that follow (Table 1).

Type of Business

The sample consisted of 14 hotels (46.7%) and 16 restaurants (53.3%), providing a relatively balanced representation of the two dominant segments of the hospitality sector. This balance is important because hotels and restaurants may differ in their sustainability challenges: hotels typically have higher energy and water demands, while restaurants produce greater levels of food-related waste. The representation of both subsectors ensures that findings reflect a broader spectrum of hospitality practices within the region (Table 1).

Years of Operation

Most establishments (66.7%) have been operating for 4–7 years, indicating a relatively young but stable industry. Only 13.3% are new entrants (1–3 years), while 20% have been in operation for over 8 years. This distribution suggests that the sector is still in a growth and consolidation phase, with many businesses likely adapting to evolving market trends, including sustainability requirements. Younger establishments may be more open to adopting innovative green practices, while older ones might face challenges related to retrofitting infrastructure to meet sustainability standards (Table 1).

Number of Employees

The vast majority of establishments (93.3%) employ only 4–6 workers, with just one establishment in each of the 1–3 employees (3.3%) and 7–10 employees (3.3%) categories. This highlights the micro-enterprise nature of the hospitality industry in the region. The predominance of small teams has implications for sustainability: while limited manpower and resources may restrict the adoption of capital-intensive initiatives (e.g., solar panels, advanced water treatment), smaller establishments may find it easier to implement low-cost, behaviourally driven measures such as waste segregation, energy conservation, and customer engagement (Table 1).

Table 1 – Frequency and percentage distribution of the profile of the respondents (Source: created by the author)

Type of Business	F	%
Hotel	14	46.70
Restaurant	16	53.30
Total	*30*	*100*
Years of Operation		
1 – 3 years	4	13.30
4 - 7 years	20	66.70
Above 8 years	6	20.00
Total	*30*	*100*
Number of Employees		
1-3 employees	1	3.30
4-6 employees	28	93.30
7-10 employees	1	3.30
Total	*30*	*100*

The dataset depicts a hospitality sector that is dominated by micro- and small-scale enterprises with limited human and financial resources, but with a relatively balanced distribution between hotels and restaurants. These structural characteristics suggest that sustainability strategies in the Iberian Peninsula's hospitality sector are likely to be pragmatic, cost-effective, and incremental rather than large-scale or technology-driven. The prevalence of younger establishments also reflects an evolving industry that may be responsive to sustainability discourse, particularly if supported by targeted training, policy incentives, and community engagement initiatives (Table 2).

Table 2 – Analysis of Energy Efficiency Practices (Source: created by the author)

Energy Efficiency Practices	Mean	DI
The establishment uses energy-efficient lighting (e.g., LED bulbs) in both guest rooms and dining areas.	4.45	Always
The establishment utilises natural ventilation (e.g., opening windows, using ceiling fans) to reduce reliance on air conditioning in both guest rooms and dining areas.	4.25	Always
Solar energy is used for lighting or water heating in the establishment's common areas, kitchens, or guest rooms where feasible.	3.17	Sometimes
The establishment reduces energy consumption by using energy-efficient cooking appliances (e.g., induction cookers, energy-efficient stoves) in the kitchen and dining area.	4.64	Always
Local, sustainable building materials such as bamboo or wood are used in the construction and renovation of the establishment to reduce energy consumption.	4.80	Always
The establishment promotes energy-saving practices by encouraging guests to turn off lights, air conditioning, and electronics when not in use in both guest rooms and dining areas.	4.80	Always
Energy-efficient appliances (e.g., refrigerators, water pumps, air conditioning units) are regularly maintained to ensure efficient operation in both lodging and food service areas.	4.25	Always
The establishment limits the use of air conditioning or electric heaters by optimising natural temperature control in guest rooms and dining areas.	4.85	Always
Energy-saving measures, such as installing timers or sensors on lights, are implemented in the guest rooms and dining areas to reduce unnecessary energy use.	3.12	Sometimes
The establishment educates both employees and guests about energy conservation practices and encourages their participation in minimising energy use.	4.71	Always
Category Mean	*4.67*	*Always*

The findings reveal a strong and consistent commitment to energy conservation across food and lodging establishments, with an overall category mean of 4.67 ("Always"). This indicates that energy-efficient behaviours are widely institutionalised, particularly those that are low-cost, behavioural, or infrastructural in nature.

High-Scoring Practices (Means: 4.71–4.85)

The highest-rated practices include limiting air conditioning and heating through natural temperature control (M = 4.85), promoting energy-saving behaviour among guests (M = 4.80), and using sustainable building materials (M = 4.80). These practices highlight a preference for practical, non-capital-intensive measures that can be integrated into daily operations with minimal financial burden. Importantly, guest engagement and staff education (M = 4.71) underscore the role of behavioural change as a central mechanism for energy efficiency in small-scale establishments.

Moderate-Scoring Practices (Means: 4.25–4.64)

Consistent use of energy-efficient cooking appliances (M = 4.64) and the regular maintenance of energy-efficient appliances (M = 4.25) reflect an operational-level focus on equipment optimisation. Natural ventilation strategies (M = 4.25) also illustrate environmentally conscious design choices that align with the local climate and reduce reliance on air conditioning.

Low-Scoring Practices (Means: 3.12–3.17)

By contrast, the adoption of capital-intensive or technologically advanced practices remains limited. The use of solar energy (M = 3.17) and automated systems such as timers or motion-sensor lighting (M = 3.12) were reported only "Sometimes." These results suggest that while establishments value sustainability, financial and technical constraints hinder the uptake of higher-cost innovations. This pattern is consistent with broader literature indicating that small-scale enterprises often prioritise operationally feasible practices over long-term technological investments (Table 3).

Table 3 – Water efficiency practices (Source: created by the author)

Water Efficiency Practices	Mean	DI
The establishment installs low-flow faucets, shower heads, and toilets in guest rooms and public areas.	4.80	Always
The establishment regularly checks for leaks in pipes, faucets, and toilets and repairs them promptly.	4.83	Always
The establishment encourages guests to reuse towels and linens during their stay to minimise water usage.	4.33	Always
The establishment collects and reuses rainwater for non-potable uses, such as landscaping or cleaning.	4.87	Always
The establishment uses water-efficient cleaning practices and tools, such as mops that require less water.	4.87	Always
Category Mean	*4.74*	*Always*

Interpretation and Implications

The data emphasise that energy efficiency in the Iberian Peninsula's hospitality sector is primarily achieved through behaviorally driven and cost-effective strategies rather than through advanced technological systems. This reliance on pragmatic measures reflects both the micro-enterprise nature of the establishments (limited manpower and financial capacity) and the importance of guest and staff engagement in achieving sustainability outcomes.

For policy and practice, the results point to a need for incentive schemes, financial support, and training programs to encourage the adoption of renewable energy and smart technologies. Without such interventions, sustainability efforts are likely to remain concentrated in low-cost domains, limiting the sector's long-term contribution to regional climate goals.

The results demonstrate a consistently high level of commitment to water conservation across establishments, with an overall category mean of 4.74 ("Always"). This indicates that water efficiency practices are well institutionalised in the hospitality sector of the Iberian Peninsula, reflecting both environmental awareness and operational pragmatism.

High-Scoring Practices (M = 4.83–4.87)

The strongest initiatives include rainwater harvesting and reuse for non-potable purposes (M = 4.87) and the adoption of water-efficient cleaning tools (M = 4.87). Regular inspection and prompt repair of leaks (M = 4.83) further highlight operational discipline and a preventative approach to water management. These results suggest that establishments prioritise practices that deliver both environmental and economic benefits, as reduced water consumption directly lowers operational costs.

Moderately Strong Practices (M = 4.33–4.80)

The installation of low-flow fixtures (M = 4.80) reflects investment in infrastructural modifications that align with global best practices in sustainable hospitality. Guest-oriented measures, such as encouraging towel and linen reuse (M = 4.33), were rated somewhat lower, suggesting variability in guest participation or in the consistency of establishments' communication strategies. While infrastructural measures are largely embedded, behavioural interventions involving customers appear less reliably enforced, potentially due to cultural attitudes or concerns about service quality.

Interpretation and Implications

The findings indicate that water conservation is treated as a core operational priority. Establishments appear to implement practices that are technically feasible, cost-efficient, and visible, such as rainwater reuse and low-flow devices, while placing slightly less emphasis on customer-driven conservation behaviours. This aligns with existing literature, which suggests that water-saving measures in hospitality are most effective when combining infrastructural improvements with active guest engagement.

Overall, the strong results highlight the proactive role of establishments in reducing water use, but also reveal untapped potential in enhancing guest awareness and participation. Policy makers and industry leaders could strengthen these efforts through training, signage, and sustainability campaigns that normalise practices like towel reuse as part of a quality guest experience rather than a cost-saving compromise (Table 4).

Table 4 – Waste management practices
(Source: created by the author)

Waste Efficiency Practices	Mean	DI
The establishment implements a comprehensive recycling program for paper, plastics, glass, and metals.	5.00	Always
The establishment separates organic waste (e.g., food scraps) from non-organic waste for composting or disposal.	5.00	Always
The establishment uses biodegradable or compostable materials for take-out containers and packaging.	4.97	Always
The establishment minimises food waste by using portion control and repurposing leftovers creatively in the kitchen.	4.97	Always
The establishment donates unused, safe food to local charities instead of throwing it away.	3.43	Often
The establishment provides staff with training on waste reduction techniques, such as efficient use of resources and reducing packaging waste.	4.93	Always
The establishment regularly monitors and tracks waste generation and uses findings for reduction and improvement.	4.97	Always
The establishment uses bulk purchasing for food and other supplies to reduce packaging waste.	4.80	Always
The establishment eliminates or reduces single-use plastic items, such as straws, utensils, and bottles, by using alternatives like reusable or paper products.	2.78	Sometimes
The establishment encourages guests to participate in waste reduction efforts, such as sorting recyclables or reducing food waste during their stay.	4.97	Always
Category Mean	*4.90*	*Always*

The data show that waste management is the most consistently and robustly implemented sustainability dimension, with an overall category mean of 4.90 ("Always"). This suggests that establishments in the Iberian Peninsula's hospitality sector have adopted waste reduction and recycling as central operational priorities, reflecting both environmental awareness and regulatory or market-driven pressures.

High-Scoring Practices (M = 4.93–5.00)

Practices such as comprehensive recycling programs (M = 5.00) and organic waste segregation for composting (M = 5.00) achieved the maximum rating, indicating near-universal adoption. Similarly, the use of biodegradable packaging (M = 4.97), portion control and repurposing of leftovers (M = 4.97), and guest participation in waste reduction (M = 4.97) highlight a strong operational and behavioural commitment to minimising waste. These results suggest that establishments prioritise visible, cost-effective, and culturally acceptable waste strategies, which also align with consumer expectations of environmentally responsible businesses.

Staff Training and Monitoring (M = 4.93–4.97)

The provision of staff training on waste reduction techniques (M = 4.93) and the systematic monitoring of waste generation (M = 4.97) illustrate institutionalised practices that extend beyond ad-hoc measures. This reflects a shift towards structured environmental management systems, where data-driven monitoring informs continuous improvement.

Moderately Adopted Practices (M = 3.43–4.80)

Bulk purchasing to reduce packaging waste (M = 4.80) is well integrated, though slightly less universal, likely reflecting differences in supply chain structures between smaller and larger establishments. Food donation programs (M = 3.43), however, are less consistently practised, possibly due to legal restrictions, logistical challenges, or liability concerns associated with distributing surplus food.

Low-Scoring Practices (M = 2.78)

The weakest area is the reduction of single-use plastics (M = 2.78), which was only "Sometimes" implemented. This result is significant given the European Union's 2021 Single-Use Plastics Directive, which bans or restricts such items. The gap suggests challenges in transitioning to alternatives, possibly due to cost implications, supply chain limitations, or resistance from both businesses and customers accustomed to convenience items.

Interpretation and Implications

Overall, the findings indicate that waste management is a core strength of sustainable hospitality in the Iberian Peninsula, with high levels of compliance in recycling, composting, staff training, and packaging alternatives. However, two critical gaps remain:

(1) underutilization of food donation initiatives, which limits potential contributions to social sustainability, and

(2) insufficient reduction of single-use plastics, which reveals a discrepancy between regulatory frameworks and actual industry practice.

Addressing these gaps requires not only greater enforcement of environmental regulations but also capacity-building initiatives-including partnerships with food banks, improved infrastructure for safe food redistribution, and financial incentives to accelerate the transition away from plastics. Strengthening these areas would move establishments beyond cost-driven waste reduction and toward more holistic, socially embedded sustainability practices (Table 5).

Table 5 – Sustainable purchasing practices and materials
(Source: created by the author)

Sustainable Purchasing Practices and Materials	Mean	DI
The establishment prioritises sourcing ingredients and products from local suppliers to reduce its carbon footprint.	4.77	Always
The establishment purchases organic and sustainably grown food products whenever possible.	4.63	Always
The establishment uses eco-friendly, biodegradable, or compostable packaging materials instead of plastic.	4.80	Always
The establishment sources seafood and meat products from sustainable and ethically responsible suppliers.	4.93	Always
The establishment prioritises purchasing cleaning products that are non-toxic, biodegradable, and environmentally safe.	4.93	Always
The establishment reduces single-use plastics by using reusable or refillable containers for condiments, toiletries, and beverages.	4.93	Always
The establishment buys furniture, fixtures, and décor made from recycled, upcycled, or sustainable materials.	2.80	Sometimes
The establishment prefers bulk purchasing to minimise packaging waste and reduce transportation emissions.	4.20	Often
The establishment ensures that paper products (napkins, tissue, and menus) are made from recycled or sustainable sources.	4.40	Always
Category Mean	*4.69*	*Always*

The results reveal a strong commitment to sustainable procurement, with an overall category mean of 4.69 ("Always"). This indicates that food and lodging establishments in the Iberian Peninsula are increasingly embedding sustainability into their supply chains, particularly in areas that directly affect daily operations and customer-facing practices.

High-Scoring Practices (M = 4.77–4.93)

The most consistently implemented practices involve sourcing ethically and sustainably produced inputs. Establishments reported very high adoption of sustainable seafood and meat sourcing (M = 4.93), the use of non-toxic and eco-friendly cleaning products (M = 4.93), and the reduction of single-use plastics through refillable or reusable containers (M = 4.93). Similarly, reliance on biodegradable packaging (M = 4.80) and prioritisation of local suppliers (M = 4.77) illustrate strong alignment with both environmental and economic sustainability goals. These practices not only minimise ecological impact but also support local economies, thereby reinforcing community-based sustainability.

Moderately Adopted Practices (M = 4.20–4.63)

The purchase of organic and sustainably grown food (M = 4.63) and bulk procurement to minimise packaging waste (M = 4.20) were rated slightly lower. These results suggest variability in market accessibility and cost considerations, as organic and bulk-purchasing systems often require stronger supplier networks and upfront investment. Nevertheless, the scores indicate that these practices are actively pursued, even if not uniformly feasible across establishments.

Low-Scoring Practices (M = 2.80)

The least adopted practice was the purchase of furniture, fixtures, and décor made from recycled or sustainable materials (M = 2.80, "Sometimes"). This gap likely reflects the capital-intensive nature of sustainable interior investments, where costs are high and immediate returns are limited. Unlike consumables such as cleaning products or food, sustainable furnishings require significant long-term investment, making them less accessible to micro- and small-scale enterprises that dominate the sector.

Interpretation and Implications

Overall, the findings suggest that establishments prioritise sustainable purchasing where it aligns with operational necessity and customer visibility, for example, food sourcing, cleaning products, and packaging. By contrast, sustainability investments in non-core, high-cost areas (e.g., furniture and infrastructure) remain underdeveloped. This pattern mirrors broader hospitality trends in which businesses adopt incremental and low-barrier practices while deferring high-capital expenditures.

The strong results in sourcing and procurement highlight a sector moving toward responsible supply chain management, yet the inconsistency in high-cost domains underscores the need for policy incentives, subsidies, or supplier partnerships to reduce barriers to adoption. Strengthening sustainable procurement in both consumables and long-term assets would ensure a more holistic approach, bridging the gap between everyday operations and long-term environmental impact (Table 6).

Table 6 – Awareness level of employees on green practices (Source: created by the author)

Awareness of employees on Green Practices	Mean	DI
How familiar are you with green practices implemented by your establishment?	4.20	Extremely Familiar
How often are you informed about the green initiatives or sustainability practices of the establishment?	3.87	Very Familiar
Have you received formal training or information about the green practices of the establishment?	3.53	Very Familiar
Category Mean	*3.87*	*Very Familiar*

The results indicate that employees possess a generally strong awareness of sustainability initiatives within their establishments, with an overall category mean of 3.87 ("Very Familiar"). This suggests that while employees are knowledgeable about green practices, there remains scope for strengthening both communication and formal training mechanisms to deepen engagement.

High Awareness (M = 4.20)

Employees reported being "Extremely Familiar" with the green practices implemented by their establishments (M = 4.20). This demonstrates that frontline staff and management are well-informed about operational sustainability measures, likely due to direct involvement in day-to-day implementation (e.g., energy conservation, waste segregation, or customer engagement initiatives).

Moderate Awareness and Communication (M = 3.87)

The frequency with which employees are updated on ongoing initiatives was rated lower (M = 3.87), suggesting that sustainability communication within organisations is somewhat irregular. While employees are aware of existing practices, the results indicate a gap in continuous reinforcement and internal messaging, which may affect motivation and consistency of implementation over time.

Formal Training (M = 3.53)

The lowest score was observed in relation to formal training or structured information sessions (M = 3.53). This suggests that most employees acquire knowledge of sustainability informally-through observation, workplace culture, or ad-hoc instructions-rather than through systematic capacity-building programs. While sufficient for general awareness, the absence of structured training limits employees' ability to critically engage with or innovate around sustainability initiatives.

Interpretation and Implications

Taken together, the data highlight that employee awareness is broad but shallow: staff know what practices exist but are less frequently engaged in structured learning or systematic communication about them. This reflects a reliance on practical, experience-based learning rather than institutionalised sustainability education.

Strengthening formal training programs and ensuring more consistent communication of sustainability goals could transform employee awareness into deeper competence and stronger commitment. Literature suggests that when employees are systematically trained in sustainability, they not only comply more effectively but also become active contributors to innovation, customer engagement, and the long-term embedding of environmental practices.

The results indicate that customers demonstrate a generally strong awareness of sustainability measures in hospitality establishments, with an overall mean of 3.93 ("Often"). While awareness is relatively high, the findings also reveal that visibility and communication of practices during visits remain inconsistent, limiting the extent to which customers fully recognise establishments' sustainability efforts (Table 7).

Table 7 – Customer Awareness on Green Practices (Source: created by the author)

Customer Awareness on Green Practices	Mean	DI
How aware are you of the green practices of the establishment?	4.23	Extremely Aware
Do you receive information about the green practices or sustainability efforts of this establishment during your visit?	3.77	Often
How often do you notice the establishment engaging in green practices during your stay?	3.80	Often
Category Mean	*3.93*	*Often*

High Awareness (M = 4.23)

Customers rated themselves as "Extremely Aware" of green practices (M = 4.23), suggesting that many enter establishments with pre-existing knowledge of sustainability principles, likely shaped by broader societal discourses on climate change and responsible consumption. This underscores the role of external social awareness in shaping consumer perceptions even before their direct experiences with an establishment.

Moderate Awareness Through Communication and Observation (M = 3.77–3.80)

However, customers reported receiving information about sustainability less frequently (M = 3.77, "Often") and noticing green practices during their stay at a similar level (M = 3.80, "Often"). These results point to a communication gap: while establishments may be implementing strong sustainability measures, these efforts are not always visible or effectively communicated to guests. This could limit the potential of green practices to serve as a differentiating factor in customer satisfaction, loyalty, and willingness to pay more—themes widely discussed in sustainable hospitality literature.

Interpretation and Implications

Overall, the data suggest that customers' awareness is driven more by general environmental consciousness than by establishments' communication strategies. This creates a perceptual gap: practices are in place, but customers are not consistently engaged or informed about them. This underutilises the opportunity to build stronger consumer trust and brand differentiation through sustainability.

To bridge this gap, establishments should adopt proactive communication strategies - such as visible signage, digital campaigns, and staff-led engagement - to make sustainability efforts more apparent. Research indicates that explicit communication of green practices not only strengthens customer awareness but also enhances satisfaction, loyalty, and willingness to support establishments that are perceived as environmentally responsible (Feng et al., 2022).

The results reveal an overall category mean of 4.46, indicating that respondents hold highly positive perceptions of green practices within their establishments. This suggests that employees and stakeholders not only recognise the presence of sustainability initiatives but also perceive them as meaningful, effective, and valuable to both the environment and the organisation (Table 8).

Table 8 – Perception of employees on green practices (Source: created by the author)

Perception of Green Practices	Mean	DI
How effective do you think the green practices of the establishment are in reducing its environmental impact?	4.53	Extremely Effective
How important do you think green practices are in improving the reputation and sustainability of the establishment?	4.27	Extremely Important
How motivated are you to follow the green practices at work?	4.53	Extremely Motivated
How satisfied are you with the green practices implemented by your establishment?	4.50	Extremely Satisfied
Category Mean	*4.46*	

Perceived Effectiveness and Motivation (M = 4.53)

Respondents rated green practices as "Extremely Effective" in reducing environmental impact (M = 4.53) and expressed equally strong motivation to follow these practices at work (M = 4.53). This dual finding highlights a strong perception–behaviour alignment, where individuals not only believe in the value of sustainability initiatives but are also personally committed to participating in them. Such alignment is critical for institutionalising sustainable practices, as motivation and perceived efficacy are key predictors of long-term behavioural compliance.

Perceived Importance for Reputation (M = 4.27)

The perception that green practices are "Extremely Important" for enhancing reputation and organisational sustainability (M = 4.27) reflects a growing recognition of the strategic value of environmental responsibility. This suggests that respondents view sustainability not merely as an ecological necessity but also as a reputational asset that strengthens competitiveness in the hospitality market.

Satisfaction with Practices (M = 4.50)

High levels of satisfaction (M = 4.50) suggest that respondents perceive existing practices as both relevant and adequately implemented. However, satisfaction may also reflect modest expectations: while establishments are clearly engaging in visible and cost-effective practices, gaps remain in the adoption of high-capital, technology-driven solutions (as highlighted in earlier analyses of energy and purchasing practices).

Interpretation and Implications

Overall, perceptions of green practices are overwhelmingly positive, suggesting that both employees and stakeholders have internalised sustainability as a core organisational value. However, the positivity of perceptions should not obscure structural limitations: favourable views may coexist with an incomplete or uneven implementation of advanced practices. These findings underscore the importance of sustaining and expanding organisational communication and training efforts, as positive perceptions provide a foundation for deepening engagement. Furthermore, aligning perceived effectiveness with measurable environmental outcomes will be crucial for avoiding "greenwashing" risks and ensuring credibility. From a managerial perspective, capitalising on employees' motivation and satisfaction offers an opportunity to position them as active ambassadors of sustainability, enhancing both operational outcomes and customer perceptions. The results yield an overall category mean of 4.07, reflecting a generally positive perception of sustainability initiatives within hospitality establishments. Customers not only express satisfaction with green practices but also acknowledge their influence on loyalty, decision-making, and willingness to pay, albeit with some limitations (Table 9).

Table 9 – Customers' Perception of Green Practices (Source: created by the author)

Customers' Perception of Green Practices	Mean	DI
How satisfied are you with the environmental practices implemented by the establishment?	4.37	Extremely Satisfied
How likely are you to recommend the establishment to others based on its environmental efforts?	3.90	Very Likely
How important are green practices to your decision to stay at the establishment?	4.10	Very Important
Do you believe that the establishment's green practices improve your overall experience during your visit?	4.10	Very Much
How likely are you to pay more for services at this establishment because of its green practices	3.90	Very Likely
Category Mean	*4.07*	

Satisfaction and Experience (M = 4.10–4.37)

Customers reported being "Extremely Satisfied" with environmental practices (M = 4.37) and affirmed that such initiatives enhanced their overall experience (M = 4.10). This indicates that sustainability is not viewed as peripheral but rather as a contributor to service quality and customer value creation. Consistent with service quality theory (Parasuraman et al., 1988), these findings suggest that environmental responsibility can be perceived as an integral dimension of service excellence.

Importance in Decision-Making (M = 4.10)

Customers considered green practices "Very Important" in influencing their decision to patronise establishments (M = 4.10). This supports the literature on environmentally conscious consumer behaviour, which highlights sustainability as an increasingly decisive factor in hospitality choice (Tennakoon et al., 2024).

Advocacy and Willingness to Pay (M = 3.90)

While customers expressed a "Very Likely" inclination to recommend establishments based on environmental performance (M = 3.90), their willingness to pay a premium scored the same (M = 3.90), indicating only moderate strength. This reflects a common challenge in sustainable hospitality: customers value green practices but may hesitate to bear additional costs, aligning with the well-documented "attitude–behaviour gap" in sustainable consumption.

Interpretation and Implications

Taken together, customer perceptions reflect a positive but cautious stance: sustainability enhances satisfaction and influences loyalty, but financial trade-offs may constrain actual consumer behaviour. Establishments may thus find that green practices strengthen reputation and differentiation, but monetising these advantages remains challenging unless accompanied by effective communication strategies that justify the added value.

For practitioners, the findings emphasise the importance of:

1) making green practices visible to strengthen satisfaction and experience;

2) framing sustainability as added value, not as an optional cost driver, to overcome resistance to price premiums;

3) leveraging customer advocacy, since positive perceptions can generate reputational benefits through word-of-mouth and online reviews.

From a scholarly perspective, the results highlight the need for further exploration of the value–action gap in sustainable hospitality and the mechanisms (e.g., transparency, trust-building, certification schemes) that may encourage customers to translate positive perceptions into stronger financial support.

Type of Business (Hotel vs. Restaurant)

The independent-sample t-test (also known as the two-sample t-test) is a statistical procedure used to determine whether there is a significant difference between the means of two independent groups (Table 10). The test assumes that the two groups are unrelated (independent) and that each participant or unit belongs to only one of the groups (Marôco, 2021).

Table 10 – Test of difference on the employees' green practices when grouped according to profile variables (Source: created by the author)

Types of Business	Mean	t-value	p-value	Decision
Hotel/ Restaurant	2.33	14.21	0.000	Reject Ho
Profile	**df**	**F**	**P-value**	**Decision**
Year of Operation				
Between Groups	2	2.05		
Within Group	27			
Number of Employees				
Between Groups	2	2.58		

For example, in hospitality research, an independent-sample t-test could be applied to compare whether hotels and restaurants differ significantly in their adoption of green practices. Here, "type of establishment" defines the two groups, and the outcome variable (e.g., mean sustainability score) is compared across them.

The logic of the test is straightforward: it examines the ratio between the difference in group means and the variability of scores within each group (Marôco, 2021). If the observed difference between group means is large relative to the variability, it is unlikely to have occurred by chance, and the null hypothesis (H_0: there is no difference between groups) is rejected.

Formally, the test statistic is expressed as:

$$t = \frac{\overline{X_1} - \overline{X_2}}{\sqrt{S_p^2\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} \tag{1}$$

Where $\overline{X_1}$ and $\overline{X_2}$ are the sample means of the two groups; n_1 and n_2 are the sample sizes; S_p^2 is the pooled variance, representing the average variability within the two groups (Marôco, 2021).

If the calculated t-value exceeds the critical value at a chosen level of significance (e.g., $p < .05$), the result indicates a statistically significant difference between the two groups.

Assumptions

The independent-sample t-test relies on three key assumptions:

1) independence of observations – the two groups are independent.

2) normality – the dependent variable is approximately normally distributed within each group.

3) homogeneity of variances – the variances of the two groups are equal (tested using Levene's Test).

If these assumptions are violated, alternative tests such as Welch's t-test or non-parametric methods (e.g., Mann–Whitney U test) can be used (Marôco, 2021).

In this study, you used the independent-sample t-test to test whether hotels and restaurants differed significantly in their sustainability practices. The results showed a significant difference ($t = 14.21$, $p < .001$), meaning that business type influences sustainability adoption.

The independent-sample t-test revealed a statistically significant difference between hotels ($M = 2.33$) and restaurants, with a t-value of 14.21 and a p-value of 0.000 ($p < 0.05$). The null hypothesis (H_0) was therefore rejected. This finding suggests that hotels and restaurants differ significantly in their adoption of environmentally friendly practices. Given the higher operational complexity and resource consumption of hotels (e.g., greater energy and water use, more diverse service offerings), it is plausible that hotels exhibit different levels of engagement with sustainability compared to restaurants, which may prioritise waste reduction and local sourcing due to food-focused operations.

Years of Operation

The one-way Analysis of Variance (ANOVA) is a statistical technique used to determine whether there are significant differences among the means of three or more independent groups (Marôco, 2021). Unlike the independent-sample t-test, which is limited to two groups, ANOVA extends the comparison to multiple categories of a single independent variable (or "factor").

For example, in this study, one-way ANOVA was employed to test whether sustainability practices varied significantly according to the years of operation (1–3 years, 4–7 years, and above 8 years) or the number of employees (1–3, 4–6, 7–10).

The logic of ANOVA is based on partitioning the total variation in the data into two components:

– between-groups variance – variation explained by differences in group means (the effect of the independent variable);

– within-groups variance – variation due to random error or individual differences within each group (Marôco, 2021).

The test produces an F-ratio, which is the ratio of the variance between groups to the variance within groups:

$$F = \frac{Mean\ Square\ Between\ Groups}{Mean\ Square\ Within\ Groups} \tag{2}$$

If the calculated F-value is sufficiently large, and the associated p-value is below the chosen level of significance (e.g., $p < .05$), the null hypothesis (H_0: all group means are equal) is rejected, indicating that at least one group mean differs from the others.

Assumptions

1. Independence of observations – groups are independent of one another.

2. Normality – the dependent variable is approximately normally distributed within each group.

3. Homogeneity of variances – the variances across groups are equal (commonly assessed with Levene's Test).

When the assumption of equal variances is violated, a more robust test such as Welch's ANOVA may be applied (Marôco, 2021).

In this research, one-way ANOVA was used to test whether differences in green practices existed across categories of years of operation and number of employees. Results indicated no statistically significant differences ($p = 0.15$ for years of operation; $p = 0.09$ for number of employees). This means that sustainability adoption was not influenced by how long establishments had been in operation or by their workforce size, but rather shaped by other contextual or sectoral factors.

A one-way ANOVA was conducted to examine differences in green practices across establishments grouped by years of operation (1–3 years, 4–7 years, and above 8 years). Results showed $F(2,27) = 2.05$, $p = 0.15$, indicating no statistically significant differences. Thus, the null hypothesis was accepted. This suggests that the length of time an establishment has been in operation does not significantly influence its adoption of green practices. The result implies that sustainability efforts are being adopted regardless of organisational maturity, possibly due to shared external drivers such as regulatory frameworks, consumer expectations, or cost-saving imperatives.

Number of Employees

The Analysis of Variance (ANOVA) is a statistical procedure used to test whether there are significant differences in the means of two or more independent groups. Whereas a t-test is limited to comparing two means, ANOVA allows researchers to assess differences across multiple groups simultaneously, thereby reducing the risk of Type I error that would occur if multiple t-tests were run independently.

The basic principle of ANOVA is to compare the amount of variance between groups (caused by the independent variable) with the amount of variance within groups (caused by random error or individual differences) (Marôco, 2021). The test produces an F-ratio, calculated as:

$$F = \frac{Variance\ Between\ Groups}{Variance\ \ Within\ Groups} \tag{3}$$

– A large F-ratio (with a p-value $< .05$) indicates that at least one group mean differs significantly from the others.

– A small F-ratio (with a p-value $> .05$) suggests that observed differences are likely due to random variation rather than a systematic effect.

Assumptions

1. Independence of observations – the groups being compared are independent.

2. Normality – the dependent variable is normally distributed within each group.

3. Homogeneity of variances – the variances of the groups are equal (often tested with Levene's Test).

If these assumptions are violated, more robust alternatives such as Welch's ANOVA or non-parametric tests (e.g., Kruskal–Wallis test) can be used.

One-Way vs. Other ANOVAs

– A one-way ANOVA tests for differences in means across categories of a single factor (e.g., years of operation: 1–3, 4–7, above 8 years).

– More complex designs include two-way ANOVA (testing for interactions between two factors) or repeated measures ANOVA (used when the same subjects are measured under different conditions).

Application in This Study

In this research, a one-way ANOVA was applied to examine whether sustainability practices differed significantly across groups based on years of operation and number of employees. The results indicated that neither factor had a statistically significant effect ($p = .15$ and $p = .09$, respectively). This suggests that sustainability adoption is not determined by organisational age or workforce size, but is likely shaped by other factors such as business type, regulatory environment, or consumer expectations.

Similarly, the ANOVA results for the number of employees revealed $F(2,27) = 2.58$, $p = 0.09$, which is also not statistically significant at the 0.05 level. The null hypothesis was accepted. This finding indicates that establishment size, as measured by workforce, does not significantly differentiate levels of sustainability adoption. The predominance of micro- and small-enterprises in the sample may explain this outcome, as most establishments have similar staff sizes (typically 4–6 employees), limiting variability between groups.

Interpretation and Implications

The inferential analysis demonstrates that the type of business is the only factor that significantly differentiates sustainability practices. Hotels and restaurants appear to engage in green practices differently, likely reflecting sector-specific demands and operational structures. By contrast, years of operation and workforce size do not significantly affect adoption, suggesting that sustainability is not merely a function of experience or scale, but instead is shaped by broader contextual factors.

From a managerial perspective, these findings suggest that sector-specific interventions may be more effective than generalised training programs. For instance, hotels may require tailored strategies that address energy and water conservation, while restaurants may benefit from stronger support in reducing food waste and promoting sustainable sourcing. Policymakers and industry associations could design differentiated sustainability frameworks to address the unique challenges and opportunities of each subsector.

Results, Interpretation, and Implications

The findings of this study provide a comprehensive picture of how food and lodging establishments in the Iberian Peninsula operationalise sustainability. The respondent profile revealed that the sector is dominated by micro- and small-sized enterprises, with most businesses employing between four and six workers and operating for four to seven years. The sample included both hotels and restaurants in relatively equal proportion, ensuring representation across the two main sub-sectors. These structural features contextualise the results: limited manpower and financial resources constrain the adoption of capital-intensive innovations, while the relatively young age of most establishments reflects a sector still consolidating its practices but showing agility in adopting low-cost, behaviourally oriented measures.

Across the four domains of sustainability practices, the results demonstrate a strong orientation toward environmental responsibility, though with varying degrees of intensity. Energy efficiency practices were widely implemented, with establishments making consistent use of LED lighting, natural ventilation, and guest engagement strategies. These practices indicate a pragmatic reliance on cost-effective solutions that are easily integrated into daily operations. However, more capital-intensive measures such as solar energy systems and automated sensors were only occasionally adopted, underscoring the structural barriers faced by small enterprises. Water efficiency practices were similarly robust, with rainwater collection, leak monitoring, and low-flow fixtures widely used. While towel and linen reuse programs were also in place, they were less consistently adopted, suggesting that customer-facing initiatives remain a relative weakness compared to infrastructural and operational measures.

Waste management emerged as the strongest domain, with comprehensive recycling and composting programs, staff training, and guest involvement all scoring near universal adoption. The practices not only reflect a strong institutionalisation of waste reduction but also indicate alignment with both environmental and cost-saving imperatives. Yet, food donation programs and the reduction of single-use plastics were notably weaker, revealing persistent challenges linked to legal restrictions, logistical barriers, and adaptation to regulatory changes such as the European ban on single-use plastics. Sustainable purchasing also scored highly, especially in the sourcing of ethical and eco-friendly products, biodegradable packaging, and non-toxic cleaning supplies. However, long-term investments in sustainable furniture and fixtures were rarely made, reflecting the capital intensity of such initiatives and the difficulty of prioritising them in resource-constrained enterprises.

Beyond operational practices, the study also examined levels of awareness and perception among employees and customers. Employees demonstrated a moderate-to-high level of awareness of sustainability practices, though much of this knowledge appeared to be acquired informally rather than through structured training. While they were generally very familiar with practices, the relatively low score for formal training highlights a gap in capacity building. Despite this, employee perceptions were overwhelmingly positive: they viewed green practices as highly effective in reducing environmental impact, as important for reputation, and reported strong motivation and satisfaction with their adoption. Customers, in turn, expressed strong general awareness of sustainability but reported only moderate recognition of practices during their visits, revealing a communication gap. Although they valued sustainability as part of their experience and decision-making, their willingness to pay more for environmentally responsible services remained limited, consistent with the well-documented attitude–behaviour gap in sustainable consumption.

Inferential analysis further clarified the patterns. Significant differences were found between hotels and restaurants, suggesting that sustainability adoption varies by subsector, likely reflecting different operational demands and cost structures. However, no significant differences were observed by years of operation or number of employees, indicating that sustainability practices are not dependent on organisational maturity or scale but are instead shaped by external drivers such as regulatory frameworks, consumer expectations, and cost-saving imperatives.

Taken together, the findings highlight that sustainability in the Iberian Peninsula's hospitality sector is rooted in pragmatic, cost-effective practices rather than advanced technological investments. Waste management emerged as the strongest domain, followed by water conservation, sustainable purchasing, and energy efficiency, the latter being limited by reliance on low-cost measures. Employees demonstrated strong motivation and positive perceptions, while customers expressed satisfaction but revealed lower levels of visibility and weaker financial commitment. These dynamics illustrate that sustainability has been embraced as a core organisational value but remains uneven in implementation and communication.

The implications are twofold. From a theoretical perspective, the study supports existing scholarship that emphasises the predominance of behaviourally driven, low-cost initiatives in small-scale enterprises and contributes to debates on the value–action gap by illustrating the disjunction between customer appreciation of sustainability and their limited willingness to pay. From a practical perspective, the findings underscore the need for capacity building through formal training for employees, stronger communication strategies to increase customer awareness, and policy interventions to support capital-intensive investments such as renewable energy and sustainable infrastructure. Sector-specific strategies are also necessary: hotels require targeted support for energy and water management, while restaurants may benefit from greater focus on food waste reduction and sustainable sourcing.

In sum, the hospitality sector in the Iberian Peninsula demonstrates both readiness and commitment to sustainability, but its progress is constrained by structural limitations and inconsistent communication. To transition from incremental, cost-saving actions to transformative change, a more systemic approach is needed that aligns business practices with policy incentives, technological innovation, and customer engagement. Only through such coordinated efforts can the sector fully contribute to regional and global sustainability goals.

Conclusions

This study examined the adoption of green practices among food and lodging establishments in the Iberian Peninsula, providing a comprehensive account of sustainability initiatives across energy efficiency, water conservation, waste management, and sustainable purchasing. The results reveal that while the hospitality sector is strongly engaged with environmentally responsible practices, implementation is uneven and shaped by structural, financial, and communicative constraints. Waste management and water conservation emerged as the most consistently applied domains, reflecting practices that are both cost-effective and operationally feasible. In contrast, energy efficiency and sustainable procurement showed gaps, particularly in capital-intensive areas such as renewable energy systems and sustainable infrastructure.

The analysis further demonstrated that employees possess high levels of motivation and positive perceptions toward green practices, though their awareness is often developed informally and not reinforced through systematic training. Customers, meanwhile, expressed satisfaction with and recognition of sustainability efforts, but their awareness during visits was limited by weak communication strategies, and their willingness to pay a premium for environmentally responsible services remained modest. Together, these findings underscore the persistence of the "value–action gap" in sustainable hospitality, in which stakeholders express support for sustainability but are hesitant or unable to translate this support into consistent behavioural or financial commitment.

Statistical analysis confirmed that differences in sustainability adoption are more strongly associated with the type of establishment (hotels versus restaurants) than with organisational size or years of operation. This suggests that sustainability strategies must be sector-specific, addressing the unique operational and environmental challenges of different hospitality formats.

Theoretically, this study contributes to scholarship on sustainable hospitality by reinforcing the argument that micro- and small-enterprises adopt pragmatic, low-cost sustainability measures rather than advanced technological solutions. It also provides empirical evidence on how employee perceptions and customer awareness interact with organisational practices, enriching debates on stakeholder engagement and sustainable consumer behaviour. Practically, the findings highlight the need for targeted capacity-building through formal training, improved communication strategies to enhance customer recognition of sustainability initiatives, and policy frameworks that provide financial incentives for high-cost innovations such as renewable energy and sustainable furnishings.

Ultimately, the Iberian Peninsula's hospitality sector demonstrates readiness and commitment to sustainability, but its potential remains constrained by resource limitations and communication gaps. To advance beyond incremental, cost-saving practices, a systemic approach is required that integrates business operations, customer engagement, and supportive public policy. Strengthening these interconnections will enable the sector not only to contribute more effectively to regional and global sustainability goals but also to position itself as a model of environmentally responsible hospitality in ecologically sensitive contexts.

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AI vs. Humans in U.S. Retail Banking: A Pilot Study on Customer Satisfaction and Service Excellence

Sifat Mahmud

Purpose. This pilot study aims to explore the perceived effectiveness of artificial intelligence (AI) and human interaction models within a university-affiliated sample, focusing on U.S. retail banking customer satisfaction and service excellence. **Design / Method / Approach**. The pilot study involved 50 participants from a university community—U.S. retail banking customers affiliated with Wright State University. A structured survey was conducted, and data were analyzed using descriptive statistics, predictive analytics, ANOVA, regression analysis, and t-tests to assess satisfaction levels, response times, and service preferences. **Findings**. Results indicate that human interaction consistently outperformed AI, with an average satisfaction score of 4.14 compared to 3.56 for AI ($p<0.05$). Male participants rated AI higher, whereas females preferred human interaction. Regression analysis revealed that AI satisfaction was primarily influenced by service consistency ($p=0.035$, $R^2=0.176$), while human satisfaction was driven by personalized service ($p=0.009$, $R^2=0.220$). These results suggest that empathy and personalization remain central to service excellence, while AI's consistency can enhance operational efficiency. **Theoretical Implications**. The findings contribute to understanding the human–AI service trade-off by integrating behavioral and demographic dimensions into service design. **Practical Implications**. The study recommends enhancing the consistency of AI-driven systems and investing in employee training programs to strengthen empathy and personalization, which together foster loyalty and customer trust. **Originality / Value**. This work empirically substantiates the dual path toward technological efficiency and human-centric empathy, highlighting hybrid AI–human approaches as optimal for banking economics. **Research Limitations / Future Research**. Limited sample size and homogeneity restrict generalization; future research should employ larger, demographically diverse samples and longitudinal designs to explore mediating factors such as trust and cultural context. **Article Type**. Exploratory Research / Pilot Study.

Keywords:

artificial intelligence, human interaction, customer satisfaction, retail banking, service excellence, hybrid AI-human models

Мета. Це пілотне дослідження спрямоване на вивчення сприйнятої ефективності моделей взаємодії штучного інтелекту (ШІ) та людини у вибірці, пов'язаній з університетським середовищем, із фокусом на задоволеності клієнтів роздрібного банкінгу США та досконалості обслуговування. **Дизайн / Метод / Підхід.** Пілотне дослідження охопило 50 учасників університетської спільноти — клієнтів роздрібного банкінгу США, пов'язаних з Університетом Райта. Проведено структуроване анкетування, а отримані дані проаналізовано із застосуванням описової статистики, предиктивної аналітики, ANOVA, регресійного аналізу та t-тестів для оцінювання рівнів задоволеності, часу реагування та уподобань у сервісних моделях. **Результати**. Виявлено, що взаємодія з людьми стабільно перевищує ефективність ШІ: середній бал задоволеності становив 4,14 проти 3,56 для ШІ ($p<0{,}05$). Чоловіки оцінювали ШІ вищими балами, тоді як жінки надавали перевагу людській взаємодії. Регресійний аналіз показав, що задоволеність ШІ визначається насамперед послідовністю обслуговування ($p=0.035$, $R^2=0.176$), тоді як людська задоволеність — персоналізованим підходом ($p=0.009$, $R^2=0.220$). Отримані результати свідчать, що емпатія та індивідуалізація залишаються ключовими для високої якості сервісу, а послідовність ШІ сприяє підвищенню ефективності процесів. **Теоретичне значення**. Дослідження поглиблює розуміння компромісу між людським і ШІ-обслуговуванням, враховуючи поведінкові та демографічні чинники у проєктуванні сервісів. **Практичне значення**. Рекомендовано підвищити послідовність роботи систем ШІ та інвестувати у підготовку персоналу для розвитку емпатії й персоналізованого обслуговування, що разом зміцнює довіру та лояльність клієнтів. **Оригінальність / Цінність**. Робота надає емпіричні підтвердження доцільності поєднання технологічної ефективності з людською емпатією, підкреслюючи переваги гібридного підходу «людина – ШІ» для банківського сектору. **Обмеження дослідження / Майбутні дослідження**. Обмеженість вибірки та її однорідність знижують рівень узагальнення результатів; подальші дослідження мають охопити ширші та різноманітніші вибірки із застосуванням лонгітюдних методів і вивченням таких чинників, як довіра та культурний контекст. **Тип статті**. Прикладне дослідження / Пілотне дослідження.

Ключові слова:

штучний інтелект, людська взаємодія, задоволеність клієнтів, роздрібний банкінг, досконалість обслуговування, гібридні моделі ШІ–людина

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The exaggerated adoption of Artificial Intelligence (AI)–driven technologies in U.S. retail banking represents a double-edged sword for the national economy (McKinsey & Company, 2021). In fact, businesses rely on AI with the expectation that it will boost efficiency and significantly reduce operational costs; however, a key concern remains: the ultimate impact on customer satisfaction. This question is particularly relevant in areas where human touch, empathy, personalization, and understanding are essential (Deloitte Network, 2024). This research investigates the effectiveness of AI versus human interaction in retail banking, focusing on their influence on customer satisfaction and service excellence. Additionally, this study addresses a persistent concern for the U.S. economy: harmonizing technological advancement with customer-centric service delivery.

Literature Review

The increasing adoption of AI technologies in retail banking has fundamentally transformed service delivery models (Scheffler & Puczyk, 2025). While AI implementations demonstrate measurable improvements in operational efficiency and cost reduction (Pattanayak, 2021), customers continue to express a preference for human interaction in complex service scenarios (Huang & Rust, 2022). This preference is particularly evident in emotionally sensitive banking interactions, such as loan applications and financial counseling (Huang & Rust, 2022). Current research identifies key demographic variations in technology acceptance, with younger male customers showing greater comfort with AI-driven services compared to older age groups (Méndez-Suárez et al., 2023). Gender differences are especially pronounced, with female customers consistently rating human interactions higher across all age ranges (Ameen et al., 2021). These findings align with broader service literature emphasizing the importance of emotional intelligence in customer satisfaction (The Contentstack Team, 2024).

AI systems currently excel in routine transactions but face challenges in addressing nuanced customer needs that require empathy and judgment (Huang & Rust, 2022). Emerging hybrid models that strategically combine AI efficiency with human empathy show promise for optimizing service delivery and customer satisfaction (Huang & Rust, 2022).

Methodology

Data Collection

A survey was conducted among participants from Wright State University's Raj Soin College of Business, focusing on key metrics such as customer satisfaction, response time for AI and human interaction, and service preferences. The survey combined quantitative measures with qualitative feedback to capture personal experiences where AI-driven technology and human interaction play roles in the U.S. retail banking system.

Data Cleaning

Survey responses were rigorously cleaned to eliminate incomplete or irrelevant entries, ensuring the reliability of the results. Numerical responses were coded to facilitate statistical analysis. Insights derived from the analysis informed actionable recommendations aimed at supporting economic efficiency in the future of the U.S. retail banking industry.

Analytical Approach

To examine the effectiveness of AI versus human interaction in U.S. retail banking, a comprehensive five-stage analytical approach was employed. This approach integrates descriptive and inferential statistics with data visualization techniques to systematically evaluate customer satisfaction, response times, service preferences, and their broader economic implications.

Descriptive Statistics were first applied to summarize central tendencies (means, standard deviations) and distributions of key variables, including customer satisfaction trends, response times, and preference distributions. This stage provided foundational insights into service dynamics and allowed identification of patterns in the data without making inferential claims, forming the basis for subsequent analyses.

ANOVA (Analysis of Variance) was used to compare mean satisfaction levels between AI and human interactions. The F-statistic, calculated as

$$F = \frac{\text{between-group variance}}{\text{within-group variance}},$$

was employed under the null hypothesis of equal means, with assumptions of normality and homogeneity of variance verified using Levene's test. This analysis identified the optimal balance of service delivery to enhance customer loyalty and informed recommendations on critical factors contributing to economic stability in the banking sector.

Regression Analysis examined the relationship between response time and customer satisfaction. Multiple linear regression models were fitted, e.g.,

$$\text{Satisfaction} = \beta_0 + \beta_1(\text{Response Time}) + \varepsilon,$$

where β coefficients represent the change in satisfaction per unit change in the predictor. Assumptions of linearity, independence, homoscedasticity, and normality of residuals were verified using scatterplots, Durbin-Watson tests, and Q-Q plots. The coefficient of determination R^2 quantified the variance explained, while p-values assessed the significance of each predictor at $\alpha = 0.05$. This stage provided insights into how operational competence impacts economic outcomes in the banking sector.

***t*-tests** were conducted to compare preferences for empathy and personalization between AI and human services. Independent samples t-tests, calculated as

$$t = \frac{M_1 - M_2}{\sqrt{(s_1^2/n_1)+(s_2^2/n_2)}}$$

assuming equal variances confirmed by an F-test, were complemented with effect size calculations (Cohen's d) to evaluate practical significance. This analysis highlighted the economic importance of trust and relationship-building in financial markets and quantified differences in customer perception between AI and human interactions.

Finally, **Data Visualization** consolidated graphical and tabular representations of all findings, including bar charts (e.g., Figure 1 for satisfaction by demographics), which facilitated clear interpretation of trends and supported data-driven decisions to improve service delivery and economic efficiency. All analyses were conducted in R (version 4.3.1), with significance defined at $p < 0.05$. The survey instrument is detailed below.

Self-Reflection on Research Scope

The present pilot study was designed to explicitly lay the groundwork for foundational insights and a methodological proof-of-concept in a specific university context. While future research would benefit from an enlarged and more diverse sample, including additional variables such as 'trust,' and more extensive statistical analyses, these elements were beyond the practical and conceptual scope of this initial investigation. The present work thus represents a critical first step, laying necessary groundwork for more extended research programs.

Survey Questionnaire

The following questionnaire aims to capture participants' experiences and perceptions of AI and human interactions in U.S. retail banking.

1. Demographic Information

– Age group: 18–22 / 22–29 / 30–39.
– Gender: Male / Female.

2. Please rate the following statements on a scale of 1–5 (1 = Strongly Disagree, 5 = Strongly Agree):

– Q1_a: AI is efficient in handling banking queries.
– Q1_b: Human representatives provide personalized service.
– Q1_c: AI responses are consistent.
– Q1_d: Human representatives demonstrate empathy.
– Q2: I am satisfied with AI interactions overall.
– Q3: I am satisfied with human interactions overall.
– Q4_a: Human interactions offer convenience and speed.
– Q4_b: Human interactions provide personalized service.
– Q4_d: Human interactions demonstrate empathy and

understanding.

– Q5_a: AI response time is satisfactory.

3. Open-ended question:

– Describe your experiences with AI and human banking interactions.

Results

This section presents the findings of the study, organized according to the three research questions. The analysis examines customer satisfaction with AI and human services, evaluates feedback on service efficiency and responsiveness, and explores preferences regarding empathy, personalization, and human-centric engagement in U.S. retail banking. The following subsections summarize both quantitative and qualitative insights from the survey, highlighting patterns in satisfaction, performance, and preferences.

Research Question 1: Customer Satisfaction

This section evaluates overall customer satisfaction with both AI-driven and human interactions in U.S. retail banking services.

Based on survey responses, a comparative analysis was conducted to examine satisfaction levels with AI-enabled automated services and human-assisted interactions across different age and gender groups.

The results indicate a consistent pattern: human interactions were generally rated higher than AI interactions, regardless of demographic category. As shown in Figure 1, the bar chart presents the mean satisfaction scores (on a 1–5 scale) for AI (Q2) and human (Q3) interactions across age–gender subgroups, demonstrating the persistent advantage of human engagement in perceived service quality.

Figure 1 – Measuring Customer Satisfaction: Evaluate overall satisfaction with both AI and human interaction (Source: Author)

The analysis of survey data reveals clear demographic patterns in perceived satisfaction with AI-based and human-based services in U.S. retail banking. The results are summarized across three analytical dimensions: **age-based movements**, **gender-based variances**, and a **grand total summary** supported by regression analysis.

1. Age-Based Movements

For respondents aged 0–22, the overall satisfaction score for AI services was 3.2, slightly lower than the 3.6 recorded for human interaction. Within this group, males rated both AI (3.33) and human (3.6) interactions higher than females (3.0 for AI and 3.5 for human).

Among participants aged 22–29, a more distinct satisfaction gap emerged. The average AI satisfaction score was 3.45, while human interaction reached 4.09. Males in this group expressed greater satisfaction with AI (4.0) than females (3.33), whereas females reported substantially higher satisfaction with human interaction (4.22) compared to males (3.5).

For the 30–39 age group, AI satisfaction increased slightly to 3.65, but human satisfaction remained higher at 4.24. Here, males rated human interaction at 4.29 and females at 4.18, while their evaluations of AI services were nearly identical (3.59 and 3.71 respectively).

2. Gender-Based Variances

Across all age categories, males generally rated AI-driven services higher than females, with one exception: in the youngest group (0–22), females expressed slightly higher satisfaction with human interaction. Conversely, females consistently rated human interaction higher in both the 0–22 and 30–39 cohorts, confirming a gender-linked tendency toward valuing empathy and personalization.

3. Grand Total Summary

When aggregated across all demographic segments, the mean satisfaction score for AI services was 3.56, compared with 4.14 for human interactions. This overall difference demonstrates a statistically and practically meaningful preference for human-based customer service in retail banking environments.

The regression model presented in Table 1 (Regression Statistics for AI Satisfaction) further supports these findings. The model yielded $R^2 = 0.176$, indicating that 17.6% of the variance in AI satisfaction can be explained by the predictors included. The analysis was statistically significant ($F(3,46) = 3.28$, $p = 0.029$), with consistency emerging as the most influential predictor ($\beta = 0.176$, $p = 0.035$). This suggests that the perceived reliability of AI systems plays a key role in shaping overall satisfaction levels.

The statistical outcomes reveal a consistent trend indicating that human interactions are generally evaluated more positively than AI-based interactions, with an average difference of 0.58 points across all respondent groups. Notable variations in satisfaction emerge when disaggregated by age and gender, particularly within the 22–29 age group, where males tend to assign higher satisfaction scores to AI interactions, whereas females provide higher ratings for human interactions. Overall, males demonstrate slightly greater satisfaction with AI services, while females describe more favorable experiences with human-assisted interactions.

Research Question 2: Customer Feedback Assessing

To assess customer feedback, the study examined how AI and human interactions are perceived in terms of satisfaction, efficiency, consistency, and response time, providing a basis for evaluating overall experience.

Based on the survey responses, regression analysis was performed on AI satisfaction, efficiency, consistency, and response time. This analysis provided a better image on overall experience. Consistency significantly improves satisfaction, while efficiency shows a marginal impact, and response time has no meaningful effect. The AI model ($R^2 = 17.6\%$) was statistically significant overall (p = 0.029). R^2 (17.6%) clarifies that 18% of the differences in customer satisfaction with AI are explained by this model. The significance F (0.029) indicates that the overall model is statistically significant, meaning the three factors—Efficiency, Consistency, and Response Time influence—combined have a real impact on satisfaction. **Key takeaways** are that consistency is the most important factor for improving customer satisfaction, efficiency might also help but its impact is less clear because it is not statistically significant in this analysis, and response time does not seem to affect satisfaction much, based on this data.

The analysis of the impact of Personalization and Empathy on satisfaction with human interaction identified empathy as marginally significant, while personalization showed no meaningful impact.

The analysis examines how human personalization and human empathy impact satisfaction with human interaction. The regression model explains 8.1 % of the variation in satisfaction ($R^2 = 0.081$), but the overall model is not statistically significant ($F = 0.137$, $p >$

0.05), indicating that the combination of Personalization and Empathy does not reliably predict satisfaction at a conventional significance level. As shown in Table 2 (Regression Statistics for Human Satisfaction), empathy demonstrates marginal significance (β = 0.248, p = 0.054), suggesting a slight positive effect on satisfaction, whereas the negative coefficient for personalization indicates a potential adverse effect and warrants further investigation into multicollinearity or contextual factors.

Key Takeaways. Empathy might have a slight positive effect on satisfaction, while personalization seems to have a negative effect on satisfaction.

Table 1 – Regression Statistics for AI Satisfaction (Source: Author)

Regression Statistics	
Multiple R	0.419580592
R Square	0.176047874
Adjusted R Square	0.122311865
Standard Error	0.632294157
Observations	50

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	3.929388538	1.309796179	3.276162099	0.029264788
Residual	46	18.39061146	0.399795901		
Total	49	22.32			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	1.771441719	0.675844419	2.621079154	0.011840515	0.411037462	3.131845976	0.411037462	3.131845976
Q1_a - AI Efficiency	0.18267135	0.094086339	1.941528937	0.058333969	-0.006714628	0.372057328	-0.006714628	0.372057328
Q1_c - AI Consistency	0.176184345	0.08115173	2.171048524	0.035123112	0.012834384	0.339534306	0.012834384	0.339534306
Q5_a - AI Response Time	0.156891371	0.140985822	1.112816659	0.271568881	-0.126898369	0.44068111	-0.126898369	0.44068111

Table 2 – Regression Statistics for Human Satisfaction (Source: Author)

Regression Statistics	
Multiple R	0.284613343
R Square	0.081004755
Adjusted R Square	0.041898575
Standard Error	0.713282139
Observations	50

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	2.107743733	1.053871866	2.07140544	0.137360451
Residual	47	23.91225627	0.50877141		
Total	49	26.02			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	3.751624884	0.539195357	6.957821203	9.47073E-09	2.66690374	4.836346027	2.66690374	4.836346027
Q1_b - Human Personalization	-0.148096565	0.118110212	-1.253884503	0.216084969	-0.385703663	0.089510534	-0.385703663	0.089510534
Q1_d - Human Empathy	0.247910864	0.125371175	1.977415165	0.053876103	-0.004303409	0.500125136	-0.004303409	0.500125136

Comparative Analysis of AI and Human Interaction – Customer Satisfaction includes metrics comparison, predictor analysis, and ANOVA tables. Table 3, Figure 2 summarizes model fit, highlighting AI's superior predictive power (higher R^2 and significance). The R-squared values indicate that AI interactions clarify 17.6% of the variance in satisfaction levels, while human interactions clarify only 8.1%. This indicates that the AI model is better at predicting satisfaction. The adjusted R-squared values show that AI still performs better than the human model. The significance F-values indicate that the AI model has a statistically significant overall model (p < 0.05), whereas the human models are not statistically significant (p = 0.1374).

Table 3 – Summary of Model Fit Metrics (Source: Author)

Metric	**AI Value**	**Human Value**
R-Squared	0.176	0.081
Adjusted R-Squared	0.1223	0.0419
Significance F	0.0293	0.1374

Figure 2 – Summary of Model Fit Metrics (Source: Author)

Table 4, Figures 3–4 details predictors, confirming consistency as the sole significant factor for AI (p < 0.05). The coefficient for efficiency (Q1_a) in AI interactions is positive, but its p-value (0.0583) is slightly above the conventional significance threshold, indicating a weak but positive relationship with satisfaction. Consistency (Q1_c) in AI interactions is statistically significant (p = 0.0351) and represents a strong driver of satisfaction.

Response time (Q5_a) metrics for AI are not significant (p = 0.2716), suggesting that response time might not strongly influence AI satisfaction levels. Regarding human interactions, the coefficient for personalization (Q1_b) is negative and not significant (p = 0.2161), implying that personalization may not strongly predict satisfaction. Empathy (Q1_d), however, shows marginal significance (p = 0.0539), indicating that empathy plays a somewhat important role in satisfaction with human interactions.

Table 4 – Predictor Analysis (Source: Author)

Factor	**Model**	**Coefficient**	**P-Value**	**Significant?**
Efficiency (Q1_a)	AI	0.1827	0.0583	No
Consistency (Q1_c)	AI	0.1762	0.0351	Yes
Response Time (Q5_a)	AI	0.1569	0.2716	No
Personalization (Q1_b)	Human	-0.1481	0.2161	No
Empathy (Q1_d)	Human	0.2479	0.0539	Marginal

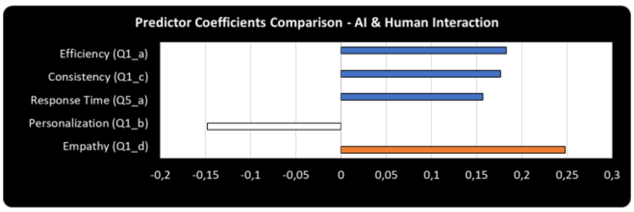

Figure 3 – Predictor Coefficient Comparison (Source: Author)

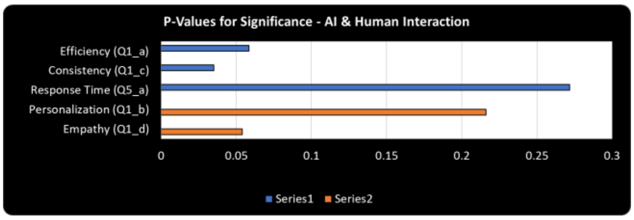

Figure 4 – P-Values for Significance (Source: Author)

For the AI satisfaction metric (Table 5), the F-value of 3.2762 with a p-value of 0.0293 confirms that the model is statistically significant, indicating that the predictors—efficiency, consistency, and response time—collectively explain satisfaction well. In contrast, for the human interaction metric, the F-value of 2.0714 with a p-value of 0.1374 suggests that the predictors—personalization and empathy—are not strong enough to explain satisfaction significantly.

Table 5 –Detailed ANOVA Table (Source: Author)

Model	df	SS	MS	F-Value	Significance F
AI	3	3.9294	1.31	3.2762	0.0293
	46	18.391	0.4		
Total	49	22.32			
Human	2	2.1077	1.054	2.0714	0.1374
	47	23.912	0.509		
Total	49	26.02			

Research Question 3: Customer Preferences

The purpose of this analysis is to understand customer preferences between AI and human interaction in retail banking branches, focusing on empathy, understanding, response time, and human personalization. A regression analysis was conducted to explore the influence of empathy, response time, and personalization on AI satisfaction. According to Table 6 (Regression for AI Preferences), the results show $R^2 = 0.041$ and $F(3{,}46) = 0.66$ with $p = 0.580$, indicating weak predictive power.

The R^2value of 4.14 % suggests that only about 4% of the variance in AI satisfaction is explained by the model, implying that other factors, such as trust in AI or user expectations, may play a more significant role. The model significance value of 0.58 confirms that it is not statistically significant, meaning empathy, response time, and personalization cannot strongly predict AI satisfaction. The empathy coefficient (0.0024) and its high p-value (0.984) further demonstrate that empathy has minimal impact within this dataset.

A key observation from this pilot study was the inconsistent effect of the personalization variable across different regression models (see Table 2 versus Table 7). Whereas in the initial model personalization was a non-significant predictor of human satisfaction, in the broader preferences model it became a significant positive predictor. This contradiction emphasizes the methodological complexity of measuring this construction and points to a critical area for refinement in further research. It suggests that the relationship between personalization and satisfaction can be highly sensitive to other variables in the model - a phenomenon that should be further investigated with a larger, more diverse sample.

Table 6 – Regression for AI Preferences (Source: Author)

Regression Statistics	
Multiple R	0.20336433
R Square	0.041357051
Adjusted R Square	-0.021163142
Standard Error	0.682019231
Observations	50

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	0.923089374	0.307696458	0.661499097	0.579967056
Residual	46	21.39691063	0.465150231		
Total	49	22.32			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	2.583344052	0.794889478	3.249941186	0.002161458	0.983314521	4.183373584	0.983314521	4.183373584
Q4_d - Empathy & Understanding	0.002391384	0.116565658	0.020515336	0.98372101	-0.232243117	0.237025884	-0.232243117	0.237025884
Q5_a - AI Response Time	0.136346932	0.155225877	0.878377591	0.384304004	-0.176106552	0.448800416	-0.176106552	0.448800416
Q1_b - Human Personalization	0.120415749	0.103819976	1.159851442	0.252094134	-0.088563024	0.329394522	-0.088563024	0.329394522

Key Takeaways.AI satisfaction is likely influenced by factors beyond empathy, response time, and personalization. Elements such as accuracy, reliability, or even trust in the AI system could be more significant in determining customer satisfaction.

Another regression analysis was conducted to examine how human empathy, convenience and speed, personalized service, and empathy and understanding influence human satisfaction in the U.S. retail banking system. A few key points from that analysis are presented below. Table 7 presents the results indicating $R^2 = 0.220$, $F(4{,}45) = 3.18$, and $p = 0.022$, with personalization found to be statistically significant ($\beta = 0.316, p = 0.010$). The R^2value of 22.02% demonstrates that the model explains about 22% of the variance in human satisfaction, suggesting that certain unaccounted factors may also influence this outcome. The significance value $F = 0.0221$ confirms that the overall model is statistically significant, implying that the factors included are meaningfully related to satisfaction levels.

Key Takeaways. Human touch plays a notably significant role in determining human satisfaction. In contrast, human empathy as well as empathy and understanding exhibit weak and statistically insignificant effects, indicating that they are not critical within this model. Similarly, convenience and speed do not appear to exert a significant impact on satisfaction.

Comparative Analysis of AI and Human Interaction – Customer Experiences. To achieve a clearer understanding of the comparison between AI and human interaction, a comparative analysis was carried out to identify which factors better predict customer experiences. Table 8, Figure 5 compares overall model fit, emphasizing the human model's stronger correlation (higher Multiple R and R^2). The Multiple R value for AI is 0.2034, which is lower than the Human Multiple R value of 0.4693, meaning human interactions have a stronger overall correlation with customer satisfaction. R-Square for AI is 0.0414, while for Human Interaction it is 0.2202, meaning the AI and Human models explain 4.14% and 22.02% of the variance in customer satisfaction, respectively. The Adjusted R-Square for AI is negative (– 0.0212), suggesting that the AI model is unfit here, whereas the Human model has a positive Adjusted R-Square (0.1509).

Table 9, Figure 6 confirms the significance of the human model (p = 0.022), in contrast to the AI model (p = 0.58). The AI model has an F-value of 0.6615 with a Significance F of 0.5800, indicating that it is not statistically significant. In comparison, the human model shows an F-value of 3.1777 with a Significance F of 0.0221, which is statistically significant. This means that human interactions have a meaningful impact on customer satisfaction, whereas AI interactions do not.

Table 10, Figures 7–8 analyzes the regression coefficients, highlighting the importance of personalization in human satisfaction (p < 0.01). For the AI model, the intercept is statistically significant (p = 0.0022), while other factors—such as Empathy &

Understanding (Q4_d) and AI Response Time (Q5_a)—have non-significant *p*-values, indicating that they do not notably influence customer satisfaction. This may imply that satisfaction with AI depends more on the correctness of outcomes than on emotional or temporal aspects.

Table 7: Regression for Human Preferences (Source: Author)

Regression Statistics	
Multiple R	0.469307789
R Square	0.220249801
Adjusted R Square	0.150938672
Standard Error	0.671467715
Observations	50

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	5.730899828	1.432724957	3.177697508	0.022076267
Residual	45	20.28910017	0.450868893		
Total	49	26.02			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	2.977028355	0.842351138	3.53418927	0.000959684	1.280446072	4.673610637	1.280446072	4.673610637
Q1_d - Human Empathy	0.142870111	0.113817726	1.255253609	0.215866235	-0.086370556	0.372110778	-0.086370556	0.372110778
Q4_a - Convenience & Speed	-0.119646168	0.135803144	-0.881026493	0.382984977	-0.393167741	0.153875405	-0.393167741	0.153875405
Q4_b - Personalized Service	0.315858923	0.117419221	2.690010376	0.009989059	0.079364472	0.552353374	0.079364472	0.552353374
Q4_d - Empathy & Understanding	-0.064905441	0.118868068	-0.546029238	0.58774282	-0.30431802	0.174507138	-0.30431802	0.174507138

Table 8 – Summary of Model Fit Metrics (Source: Author)

Metric	AI Value	Human Value
Multiple R	0.2034	0.4693
R-Square	0.0414	0.2202
Adjusted R-Square	-0.0212	0.1509
Standard Error	0.682	0.6715
Observations	50	50

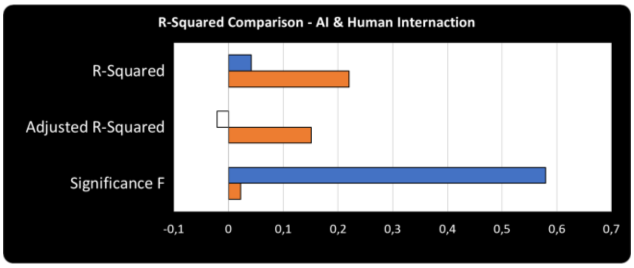

Figure 5 – *R*-Squared Comparison (Source: Author)

For the human model, Personalized Service (Q4_b) emerges as the only significant predictor of satisfaction, with a positive coefficient of 0.3159 and a *p*-value of 0.00999, showing a clear positive impact on satisfaction. In contrast, Human Empathy (Q1_d) and Convenience & Speed (Q4_a) are not statistically significant (p = 0.2159 and 0.3830, respectively), suggesting that these factors exert minimal influence on customer satisfaction.

Table 9 – ANOVA Summary (Source: Author)

Model	df	SS	MS	F-Value	Significance F
AI	3	0.9231	0.308	0.6615	0.58
	46	21.397	0.465		
Total	49	22.32			
	df	**SS**	**MS**	**F-Value**	**Significance F**
Human	4	5.7309	1.433	3.1777	0.0221
	45	20.289	0.451		
Total	49	26.02			

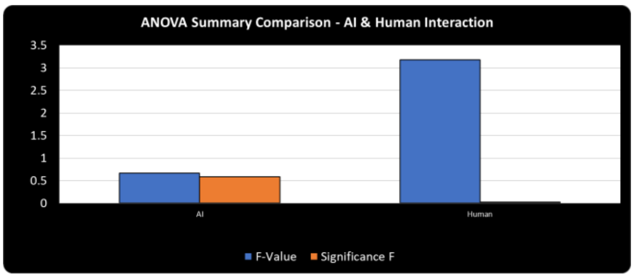

Figure 6 – ANOVA Summary Comparison (Source: Author)

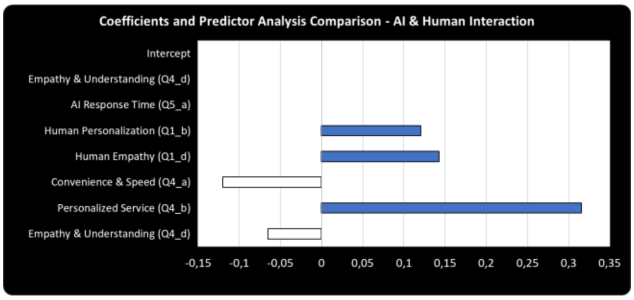

Figure 7 – Coefficients and Predictor Analysis Comparison (Source: Author)

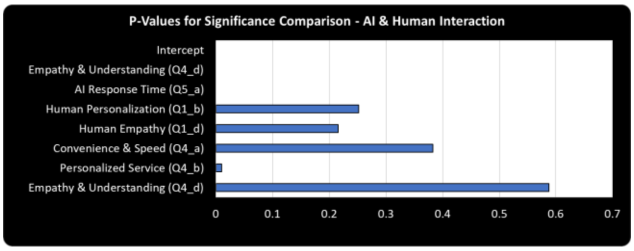

Figure 8 – *P*-Values for Significance Comparison (Source: Author)

Discussion

The assessment of customer satisfaction encompassed both AI and human interactions. Given that AI satisfaction consistently scores lower, further investigation into user preferences and the inherent limitations of AI-based interactions appears warranted, particularly within the context of the U.S. retail banking system. Additionally, considering demographic strategies—such as accounting for age and gender—may enhance the design of both AI systems and human-centered services.

These demographic patterns are consistent with findings reported by Méndez-Suárez et al. (2023), which support the implementation of segmented service strategies: AI solutions may be more effective for efficiency-driven younger male cohorts, whereas human interactions remain preferable for empathy-oriented female and older customer groups. Such differentiation could optimize economic outcomes, including customer loyalty.

Notably, younger males tend to rate AI performance higher, indicating greater openness or comfort with AI-driven technologies. Future studies should further examine the comparative quality of AI and human interactions, with particular focus on AI's conversational competence and its effectiveness in problem-solving.

Table 10 – Coefficients and Predictor Analysis (Source: Author)

Factor	Model	Coefficient	Standard Error	t Stat	P-Value	Yes
Intercept	AI	2.5833	0.7949	3.25	0.0022	No
Empathy & Understanding (Q4_d)	AI	0.0024	0.1166	0.021	0.9837	No
AI Response Time (Q5_a)	AI	0.1363	0.1552	0.878	0.3843	No
Human Personalization (Q1_b)	Human	0.1204	0.1038	1.16	0.2521	No
Human Empathy (Q1_d)	Human	0.1429	0.1138	1.255	0.2159	No
Convenience & Speed (Q4_a)	Human	-0.1196	0.1358	-0.881	0.383	Yes
Personalized Service (Q4_b)	Human	0.3159	0.1174	2.69	0.00999	No
Empathy & Understanding (Q4_d)	Human	-0.0649	0.1189	-0.546	0.5877	

Assessing Customer Feedback: AI or Human. Customer feedback was assessed in terms of satisfaction with AI and human interactions, focusing on efficiency, consistency, and response time, which together shape the overall experience. The analysis emphasizes the need to improve consistency in AI-driven technologies and services, as this factor has the strongest and most reliable impact on satisfaction. Attention should also be given to efficiency, since it represents an area with potential for improvement.

Comparative Analysis of AI and Human Interaction. In the comparative context, AI-driven technologies in the U.S. retail banking system should concentrate on improving efficiency and response time to enhance overall customer satisfaction. At the same time, organizations may invest more in employee training to strengthen empathy, which is approaching significance and could foster better development of human interaction–related services.

The regression results (Tables 1–2) underscore the role of consistency in AI models ($R^2 = 0.176$) compared with personalization in human models ($R^2 = 0.220$), supporting hybrid approaches (Huang & Rust, 2022) that balance cost efficiencies with relational value in banking economics.

Conclusions

Drawing on large-scale studies of U.S. retail banking, human contact continues to hold a significant advantage in delivering customer satisfaction over AI-based services by 0.58 points. This distinction is demographically sensitive, with a clear preference for human contact among women across all age ranges, with those aged 30–39 showing the strongest preference (mean = 4.24), whereas young men (22–29) are more tolerant of AI. Drivers, in turn, further elucidate this difference: AI effectiveness is most correlated with consistency, whereas human effectiveness is strongly correlated with individualized service, with empathy itself bordering on statistical significance. Economically, the far greater explanatory power of human interaction (R^2 = 22% versus 4% for AI) suggests that underlying forces such as trust and relationship building disproportionately influence customer loyalty. Thus, for policymakers and bankers the road ahead is twofold: optimizing AI for uniformity in automated systems and investing in human capital to provide hyper-personalized service, particularly for key demographic segments. Finally, as AI brings incremental efficiency benefits, the findings endorse that human connection remains the primary driver of increased satisfaction, implying a hybrid future—consistent with the "Caring Machine" concept—where technology enhances human emotional intelligence rather than replacing it to foster loyalty and economic security (Huang & Rust, 2022).

Limitations

First and foremost, being a pilot study, the greatest limitations lie in its scale and scope. A clear acknowledgement of these limits is important to avoid any potential misinterpretation of its results and to frame correctly the contribution this makes as a first step. The study has a low sample size, $n = 50$, exclusively drawn from a university population; thus, findings explicitly have limited generalizability. The use of convenience sampling introduces a risk of selection bias, while self-reported measures may be affected by recall errors. The cross-sectional design also precludes causal inference, and uncontrolled factors (e.g., prior AI exposure) may confound the results. Future studies should address these limitations through larger and more diverse samples, complemented by longitudinal research designs.

Future Research

The insights gained from this pilot study highlight a very clear direction in which further research should go. The next logical step involves the verification of these findings with at least a sample size of *500* participants, with diverse characteristics, using longitudinal measures that allow for tracking satisfaction over time. With a more robust foundation like that, future hybrid AI-human models could examine key critical variables such as trust and cultural influence. Meanwhile, advanced analytical techniques, such as structural equation modeling, could be utilized to unpack complex mediation effects, including, but not limited to, examining whether empathy acts as a mediator of the personalization and user satisfaction relationship. This multi-phase research agenda would go a long way in strengthening the applicability and impact of this study to U.S. banking innovation and policy.

Conflicts of Interest

Since this is a self-authored manuscript, no conflict of interest exists.

Informed Consent Declaration

This research involved human participants. As a pilot study, the population size was intentionally kept small ($n = 50$) to ensure feasibility. The participants were drawn from both graduate and undergraduate students at Wright State University.

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Pricing dilemmas in the context of consumer welfare

Nataliya Krasnikova

Purpose. The article explores conflicting approaches to pricing in the context of consumer welfare, in particular assessing the economic, psychological and behavioural aspects of the impact of price on consumers' sense of fairness, satisfaction and happiness. The main objective is to stimulate scientific discussion on the conceptualisation of the category of ‘price welfare’ and to propose a new analytical framework for interdisciplinary analysis. **Design / Method / Approach.** Within the discussion format, a critical literature review method was used, covering more than 20 peer-reviewed publications over the past two decades. Classic and modern models of price assessment from the perspective of welfare are compared, and the evolution of concepts of price fairness, rationality, and hedonic reactions is analysed. **Findings.** The article demonstrates that there is no single universal logic for the formation of consumer welfare in the field of pricing. Different types of prices - personalised, fair, differentiated - have an ambiguous impact on emotional, behavioural and economic reactions. A ‘price triangle of welfare’ is proposed, combining market efficiency, psychological perception and social legitimacy of price. **Theoretical Implications.** The material deepens the understanding of the concepts of price ethics and welfare in the context of the interdisciplinary intersection of economics, behavioural sciences and social philosophy. **Practical Implications.** The proposed framework can be applied in shaping companies' pricing policies, assessing the impact of personalised pricing on consumers, and providing analytical support for government consumer protection policies. **Originality / Value.** For the first time, three approaches to pricing have been structurally integrated with a focus on consumer happiness, allowing new hypotheses to be formulated regarding the role of price as a driver of well-being. **Research limitations / Future research.** The work does not contain its own empirical research, but instead offers conceptual foundations for future quantitative measurement of the impact of price on well-being. It needs to be expanded in the context of regional differences and cross-cultural perceptions of price. **Article type.** Discussion paper.

Keywords:

price triangle of well-being, price fairness, consumer well-being, behavioural economics, personalised pricing

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Мета. Стаття досліджує суперечливі підходи до ціноутворення в контексті споживчого добробуту, зокрема оцінює економічні, психологічні та поведінкові аспекти впливу ціни на відчуття справедливості, задоволення та щастя споживача. Основна мета - стимулювати наукову дискусію щодо концептуального оформлення категорії “цінового добробуту” та запропонувати нові аналітичні рамки для міждисциплінарного аналізу. **Дизайн / Метод / Підхід.** У межах дискусійного формату застосовано метод критичного огляду літератури, що охоплює понад 20 рецензованих публікацій за останні два десятиліття. Порівнюються класичні та сучасні моделі оцінки ціни з позиції добробуту, а також аналізується еволюція концепцій цінової справедливості, раціональності та гедоністичних реакцій. **Результати.** Стаття демонструє, що у сфері ціноутворення немає єдиної універсальної логіки формування споживчого добробуту. Різні типи цін – персоналізовані, справедливі, диференційовані – мають неоднозначний вплив на емоційні, поведінкові та економічні реакції. Запропоновано «ціновий трикутник добробуту», що поєднує ринкову ефективність, психологічне сприйняття та соціальну легітимність ціни. **Теоретичне значення.** Матеріал поглиблює розуміння концептів цінової етики та добробуту в контексті міждисциплінарного перехрестя економіки, поведінкових наук і соціальної філософії. **Практичне значення.** Запропоновані рамки можуть бути застосовані у формуванні цінової політики компаній, при оцінці впливу персоналізованого ціноутворення на споживачів, а також в аналітичній підтримці державної політики захисту прав споживачів. **Оригінальність / Цінність.** Уперше здійснено структурну інтеграцію трьох підходів до ціни з фокусом на щасті споживача, що дозволяє сформулювати нові гіпотези щодо ролі ціни як носія добробуту. **Обмеження дослідження / Майбутні дослідження.** Робота не містить власного емпіричного дослідження, натомість пропонує концептуальні засади для майбутнього кількісного вимірювання впливу ціни на добробут. Потребує розширення у контексті регіональних відмінностей та міжкультурного сприйняття ціни. **Тип статті.** Дискусійна стаття.

Ключові слова:

ціновий трикутник добробуту, цінова справедливість, споживчий добробут, поведінкова економіка, персоналізоване ціноутворення

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Pricing as an economic mechanism determines the availability of goods and services and significantly influences consumer decisions in a competitive market. Basic pricing models focus on behaviour through supply and demand and profit maximisation. In recent years, interdisciplinary approaches linking the price formation process to subjective consumer well-being have been increasingly developed (Kallus & Zhou, 2021; Diadyk & Danylenko, 2023). This creates a new platform for discussion: what dilemmas arise when prices begin to affect happiness and life satisfaction.

Contemporary research argues that price fairness plays a significant role in user perception. The perception of a fair price indirectly shapes satisfaction (Livia & Hendratmoko, 2024) and can influence loyalty (Dinanti et al., 2024). These results are important from a behavioural economics perspective because they demonstrate that market decisions have psychological consequences. At the same time, research on personalised pricing shows that price differentiation can violate fairness, reducing consumer welfare (Döpper & Rasch, 2024; Dubé & Misra 2023; Houba et al., 2022).

This discussion is becoming increasingly important in light of the emergence of digital technologies that enable price personalisation. Such technologies create both benefits for firms in the form of revenue and potential risks to consumer welfare through perceptions of unfairness (Kallus & Zhou, 2021; Faizi, 2025; Turatti, 2025). In this context, research that examines pricing dilemmas in the context of consumer welfare is highly relevant to the interdisciplinary dialogue between economic, behavioural and social sciences. **This work outlines a central question**: how do different pricing approaches (traditional versus personalised) shape perceptions of fairness, behavioural responses, and subjective well-being?

Economic approach: the consumer in the optimal pricing system

Economic pricing theory has long viewed price as a neutral transmitter of information that ensures equilibrium between supply and demand. Starting with the classical models of Walras and Marshall, researchers assumed that under conditions of perfect competition, price acts as a fair and effective tool for resource allocation (Arrow & Debreu, 1954). Within the neoclassical paradigm, welfare was understood as the sum of marginal utilities, the maximisation of which is directly related to the quantity of goods purchased at a given price. This became the basis for numerous models of optimal pricing, including price discrimination models designed to exhaust consumer surplus in favour of the producer (Varian, 1987).

The emergence of digital technologies and the growth of data volumes have significantly transformed traditional approaches. Algorithmic personalized pricing offers a new logic of well-being based not only on universal access to goods, but also on the ability of technologies to adapt prices to the individual purchasing power of consumers (Kallus & Zhou, 2021). These models allow for the creation of 'individual surplus,' which theoretically optimises utility for each consumer individually. However, this idealised picture ignores a number of ethical, regulatory, and informational constraints. These aspects are the focus of contemporary research, which shows that personalised pricing often contradicts the principles of distributive justice and creates asymmetry in access to goods (Chen, 2021; Chen et al., 2021; Coleff & Rubbini, 2023).

Classic critics of the economic approach emphasised that welfare cannot be reduced to the market: it is shaped by moral, political and institutional factors (Sen, 1995). In particular, the criticism of first-degree price discrimination models is that, although they ensure efficiency from the producer's point of view, they do not guarantee the social legitimacy of pricing policy, especially in the health, transport or energy sectors (Stole, 2007; Sharashenidze et al., 2025). Contemporary welfare theorists emphasise the need to consider social benefits, mutual consent and procedural fairness in the assessment of pricing practices (Fleurbaey, 2009; Ferranna et al., 2024). This leads to a shift in emphasis from maximising utility to analysing the fair distribution of welfare, which becomes particularly important in the context of algorithmic demand management.

Taking these evolutionary shifts into account, a new analytical task arises: to rethink the very essence of price as a carrier of value in the digital age. In response to the limitations of neoclassical models, an ethical-economic framework is proposed that combines the instrumental efficiency of price with its normative dimension. According to this framework, consumer welfare is formed not only on the basis of purchasing power, but also through the perception of fairness, transparency and participation in pricing decisions. In such a model, the market price ceases to be a 'neutral value' and acquires the meaning of a social signal, which is interpreted through the prism of trust, experience, and moral expectations.

Psychological approach: price as a cognitive and emotional stimulus

The psychological approach to pricing radically reinterprets the role of price in the consumption process. Unlike the economic paradigm, where price is seen as an objective variable, in psychology it is viewed as a subjective informational and emotional category. These ideas were first substantiated within the theory of cognitive evaluation, according to which price can serve as a sign of quality, risk or status (Monroe & Krishnan, 1985). It was established early on that consumers often do not perceive price in absolute terms, but instead use relative assessments based on previous experience, comparison and expectations.

The concept of price fairness plays a key role in modern psychological analysis, which is studied through the prism of emotional response. A price is considered unfair not only when it is too high, but also when the balance between effort and reward is disturbed, or when comparison with other consumers causes feelings of deprivation (Kahneman et al., 1986; Makedon et al., 2022). Experimental studies show that perceiving a price as unfair reduces the level of satisfaction with a purchase, weakens the emotional connection with the brand and, in some cases, causes a feeling of deception even when the deal is rationally advantageous (Xia et al., 2004).

Contemporary psychological literature focuses on the relationship between price judgement, emotions and life satisfaction. It has been proven that price reactions are primarily affective, and that it is the emotional valence of the price, rather than its level, that is the key factor in shaping well-being (Livia & Hendratmoko, 2024). It has also been established that the perception of price fairness is closely correlated with satisfaction and overall consumer happiness, even under identical purchase conditions (Dinanti et al., 2024).

At the same time, the psychological approach is not without controversy. Its strength lies in its sensitivity to context, but it is this flexibility that complicates the formalisation of models and hinders normative use. Most experiments are conducted in laboratory conditions, where simulated situations may not reflect real preferences (Grewal et al., 1994). In addition, there is a cultural problem: perceptions of price fairness or unfairness can vary significantly between countries or consumer groups, calling into question the universality of conclusions.

Nevertheless, the psychological approach is key to constructing new hypotheses about well-being, particularly through the concept of emotional price effectiveness. Within this model, price is seen as a self-regulatory tool capable of evoking feelings of control, predictability, or social recognition. Thus, price ceases to be merely a sign of loss and instead becomes a means of identity, status, and belonging. The psychological model allows us to link pricing strategies not only to behaviour but also to long-term emotional well-being - something that often escapes the attention of economists.

Behavioural approach: systematic deviations from rationality in the perception of prices and happiness

The behavioural approach to pricing and consumer welfare is based on the assumption of systematic cognitive biases that distort both economic thinking and emotional satisfaction. The basic postulates of classical economics, according to which consumers maximise utility based on stable preferences, are being revised as a result of discoveries in behavioural economics, which began with the work of Tversky and Kahneman. In particular, it has been shown that consumers are prone to the endowment effect, the anchoring effect, the framing effect, and representation heuristics (Tversky & Kahneman, 1974), which has direct implications for price perception.

From a behavioural point of view, price is not a stable characteristic of a product, but rather is subject to subjective interpretation depending on how it is presented. For example, Ariely's (2008) research shows that even absurd initial anchors can change consumers' willingness to pay. In turn, presenting a price as a discount, membership fee, or donation can lead to radically different assessments of fairness and well-being. Thus, the behavioural approach reveals price as a manipulative resource that affects happiness not so much through financial loss as through the cognitive framing of the transaction.

Contemporary behavioural literature pays particular attention to the effect of hedonic adaptation, according to which the satisfaction derived from purchases or discounts is temporary (Frederick & Loewenstein, 1999). This calls into question the permanence of the link between lower prices and long-term consumer happiness. Conversely, some studies (Das et al., 2023) show that conscious overpayment, when consumers pay more for charitable purposes or for the sake of principle, contributes to higher levels of satisfaction and well-being. The behavioural paradox is that consumers do not always want to pay less - they want to pay fairly, meaningfully and in a socially significant way.

At the same time, it is important to note that the behavioural approach avoids universal laws and instead offers a multitude of situational scenarios. This is its weakness: the explanatory power of individual effects is often contextual and not always replicated in experimental studies (Wells et al., 2017). Moreover, the abuse of pricing heuristics can lead to manipulation by the seller, which can potentially harm well-being, even if the consumer is not aware of this at the time of purchase.

The behavioural approach requires improvement of the theoretical framework, which would combine cognitive distortions with emotional valence and social expectations. The introduction of the concept of price reflexivity - the consumer's ability to critically reflect not only on the amount of expenditure but also on its symbolic, moral and identity implications - is promising. In this context, price is no longer just an object of subconscious reaction - it becomes an instrument of active self-expression that influences long-term parameters of well-being, such as dignity, autonomy and moral satisfaction.

Table 1 compares approaches to pricing in the context of economic well-being according to various criteria, clearly demonstrating the differences between theoretical approaches.

Table 1 – Comparison of pricing approaches in the context of consumer welfare (Source: created by the author)

Criterion	Economic approach	Psychological approach	Behavioural approach
Key goal	Maximizing efficiency through balancing supply and demand; optimizing welfare	Formation of a positive perception of price; support of emotional comfort	Taking into account real patterns of consumer behaviour, taking into account distortions
Attitude towards justice	Justice as a result of the competitive mechanism; market equilibrium	Subjective sense of justice; important role of interpersonal comparison	Justice as a result of context, framing, expectations, and cultural norms
Taking into account emotional reactions	Not taken into account, considered irrelevant for modelling	Emotions are a key channel for price to influence satisfaction	Emotions are considered to be the result of cognitive distortions and interpretations
Regulatory sensitivity	Low: the market is self-regulating through competition	Medium: allows for price intervention to maintain trust	High: demand for consumer protection from manipulative pricing strategies
The ontological nature of price	Objective, market value, carrier of value	Subjective information cue related to expectations	A design sensitive to presentation, context, and bias
Key welfare variable	Consumer surplus	Emotional satisfaction, perception of justice	Feeling of control, social acceptance, avoidance of dissonance
Focus on the time horizon	Short-term exchange efficiency	Medium-term impact on loyalty	Long-term impact on self-identity and moral satisfaction
Weaknesses	Ignores subjectivity and moral legitimacy	Complexity of formalization; cultural variability	High contextuality; difficulty in reproducing effects
Typical application area	Energy, competitive markets	Services, brands, socially significant products	E-commerce, charitable models, media, markets with social resonance
Potential threat to welfare	Monopoly, excessive discrimination, inflation	Failure to consider expectations and cultural differences	Manipulation, abuse of heuristics, framing
Political implications	Minimum regulation; emphasis on competition	The role of ethical branding and educational programs	The need for regulatory protection

The table illustrates a systematic comparison of three approaches to pricing - economic, psychological and behavioural - through the prism of their impact on consumer welfare. The generalization of the data allows us to highlight the differences between them not only in key variables and time horizon, but also in the ways of interpreting the nature of the price itself. If the economic perspective treats price as an objective market value, then the psychological one endows it with a subjective dimension related to trust and emotional reaction, while the behavioural one emphasizes its constructive and contextual nature. These differences shape different models of welfare: from an emphasis on consumer surplus (economic approach) to emotional satisfaction and perception of justice (psychological approach) and a sense of control and social recognition (behavioural approach).

The economic approach mostly operates with long-term models oriented towards equilibrium and efficiency, which allows to predict macroeconomic consequences, but it often ignores situational changes in consumer behaviour. The psychological approach, on the other hand, focuses on the short-term dimension, emphasizing the role of trust, emotions and cognitive reactions to prices. Its weakness lies in the limited generalization of the results - excessive attachment to the cultural and individual context makes it difficult to form universal conclusions. The behavioural approach occupies an intermediate time horizon, taking into account both instant reactions (for example, the “anchor” effect or the frame effect) and cumulative social patterns that manifest themselves in the medium term. Its weakness is the instability of the results: in different environments the same mechanisms can lead to opposite effects, which reduces the accuracy of the forecast. In general, the economic perspective provides systematicity, but is too abstract; the psychological one deepens the understanding of individual perception, but is too fragmented; behavioural combines contextuality and flexibility, but is prone to over-reliance on empirical cases.

In economic logic, welfare is considered as a function of the efficiency of resource allocation, but its potential limitation is that social justice and inequality are left out of the model. This creates a political implication in which government decisions tend to gravitate towards market liberalization and deregulation, and correction instruments (subsidies, price controls) are interpreted as distortions. In the psychological approach, welfare is limited by the emotional and cognitive ability of the consumer to respond adequately to prices: excessive complexity of tariffs or manipulative pricing practices can reduce trust and undermine the feeling of welfare. The political implications of this approach are rather statist, as they require the state to create a regulatory framework to protect the consumer from information overload and psychological distortions. The behavioural approach reveals potential limitations in the form of social norms and collective biases: group effects can increase inequality and stimulate irrational copying of other people's decisions, which limits individual welfare even in formally competitive markets. In political terms, this leads to hybrid implications: some policies gravitate towards soft interventions ("nudges", information campaigns), while others require direct intervention to prevent mass distortions. Thus, the spectrum of limitations on welfare extends from the market abstraction of the economic approach to the psychological vulnerability of the individual and the social traps of behavioural interaction, which reveals the polarity of political implications: from deregulatory freedom to normative control and hybrid strategies.

In summary, none of the approaches is self-sufficient: the economic one provides a rational basis for modelling efficiency, the psychological one takes into account the intrinsic quality of the consumer experience, and the behavioural one allows us to identify and minimize the risks of manipulation. Thus, the comprehensive integration of these perspectives creates a broader analytical field for understanding both threats and opportunities in the field of pricing, especially in the context of the growing importance of social trust, ethical standards, and global challenges.

Discussion

Summing up the three analytical traditions - economic, psychological and behavioural — it can be argued that the modern understanding of the impact of price on consumer welfare has evolved significantly. Price is no longer just a mechanism for allocating scarce resources or a marker of utility. It acts as a multi-level communicative tool that accumulates economic expediency, moral judgment and emotional-behavioural response. In this regard, the task of integrating paradigms arises, capable of providing a holistic answer to the question of the mechanisms of the impact of price on satisfaction and subjective welfare.

On the one hand, modern algorithmic price models can increase market efficiency through fine-tuning to willingness to pay; on the other hand, they undermine the prerequisites of transparency, equality and predictability, which are the basis for a subjective sense of well-being (Kallus & Zhou, 2021). Justice ceases to be a collective convention and becomes a personal experience, which makes standardized regulation difficult.

At the same time, psychological and behavioural literature emphasizes the dynamics of pleasure: price affects happiness not only through the transaction, but also through post-facto mechanisms of reflection, comparison, public discussion, and moral self-representation. That is, transactional fairness is increasingly transforming into existential fairness, within which the act of purchase is also an act of value choice. Such a shift requires a theoretical update of the framework of well-being that would go beyond utilitarianism or affective hedonism.

Against this background, a new research hypothesis emerges: the perception of price as a moral choice has a longer-term impact on pleasure than the amount of expenditure itself. This opens up the prospect of the concept of price reflexivity – the ability of the consumer to reflect not only on "what I got for my money", but also on "what role I played as a social actor through my payment". In this aspect, practices such as pay-what-you-want, charity pricing, or transparency pricing appear to be not only marketing tools, but also mechanisms for creating well-being through socially meaningful choices.

Finally, the current crisis of confidence in prices as indicators of value – manifested in the reaction to dynamic tariffs, "hidden" fees or algorithmic manipulation - requires not only regulatory regulation but also a research-based reassessment of the role of price itself in the economics of happiness. There is a need for a transdisciplinary framework that would unite efficiency analytics (economics), subjective experience (psychology) and behavioural patterns of decision-making. Such an approach would allow us to move beyond the "price as a burden" / "price as a benefit" dichotomy to a model in which price is a value communication between the market, the consumer and society.

One possible direction of integration is the proposed model of the "price triangle of well-being" (Fig. 1), where price is interpreted as the intersection of three vectors: (1) functional utility (rational cost of the product relative to alternatives), (2) cognitive fairness (expected ratio of costs and social context), and (3) affective resonance (emotional perception of costs). Such a model allows not only to explain the variability of consumer reactions, but also to predict potential sources of dissatisfaction even in the case of an objectively profitable transaction.

Another integrative approach is the concept of price legitimacy, borrowed from institutional theory. In this perspective, consumer acceptance of a price depends on its compliance not only with individual expectations but also with social norms, transparency of formation and clarity of sources of value. Thus, the reaction to the price becomes an indicator of trust in the market, and the price itself is a channel of institutional signal, like a brand or a license.

The political implications of such a rethinking are significant. First of all, it is necessary to expand the scope of responsibility of pricing policy from the domain of economic regulation to the infrastructure of welfare. In particular, state regulation of prices - for example, in the field of health services, education or basic food products – should take into account not only indicators of affordability, but also parameters of perceived fairness, which have a long-term impact on the level of satisfaction of the population.

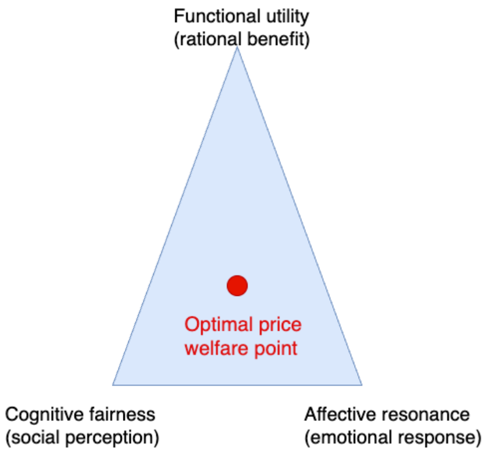

Figure 1 – Visualization of the "price triangle of welfare" model (Source: created by the author)

Second, digital personalized pricing poses a new challenge for public policy. Currently, most jurisdictions view such practices primarily from the perspective of privacy or competition law. However, given the psychological effects of personalization (perceptions of discrimination, deception, manipulation), it is worth considering the social justice of personalized pricing as a separate regulatory priority. This could include mandatory adaptive price labelling, the right to a fixed price upon request, or mechanisms to control differentiation in sensitive sectors.

The third implication concerns the educational and institutional role of the state and non-state actors in increasing the price literacy of the population. Empirical evidence suggests that most consumers underestimate real costs, hidden payments, or price traps, which directly affects satisfaction and happiness (Matte et al., 2021). The creation of transparent price breakdown tools, the dissemination of standard benefit/risk assessment models, or price ethics indices are policy areas that require systemic development.

Finally, for the scientific community, such integration poses the task of developing an interdisciplinary price well-being index - a metric that would simultaneously take into account accessibility, predictability, fairness, psychological comfort and emotional attitude to price. Such an index can become not only a research tool, but also part of the monitoring systems of public policy or corporate social responsibility strategies.

Thus, the discussion around price as a factor of well-being is not only an academic issue, but also a prerequisite for reforming approaches to economic management, digital regulation, behavioural interventions and measuring progress in well-being in the 21st century.

Conclusions

Pricing has ceased to be solely a tool for calculating the cost of a product or service, but has instead transformed into a complex socio-economic signal that affects the level of satisfaction, fairness and well-being of the consumer. According to the analysis, none of the approaches - economic, psychological or behavioural - is sufficient to explain the full range of consumer reactions to price. The level of satisfaction, as shown in the previous sections, is formed as a result of the simultaneous interaction of rational expectations, emotional assessments and social context.

Economic concepts, based on the assumptions of rationality and utilitarianism, allow for accurate modelling of exchange parameters and optimization problems, but show limited sensitivity to individual or situational factors in price perception. Psychological and behavioural approaches, in turn, open space for interpreting subjective consumer reactions, but often operate with methodologically complex or difficult to reproduce variables. This fragmentation of theoretical foundations creates gaps in understanding how price can serve as an indicator not only of value, but also of dignity, respect, or trust - especially in the areas of personalized pricing, digital commerce, or ethical consumption.

The results of the comparative analysis prove the feasibility of integrating approaches into a new framework, which can be described as a price triangle of well-being. This model combines three key elements: functional utility, cognitive fairness, and affective resonance. Achieving a balance between them forms an optimal zone of price perception, which can serve as an analytical criterion in the design of marketing, regulatory, and ethical strategies. The practical application of this model potentially allows us to redefine the categories of 'overpriced,' "fair" or 'attractive' prices in terms of welfare, rather than just purchasing power.

Of particular relevance is the study of the behavioural aspects of international pricing in the context of protracted crises, particularly the full-scale war in Ukraine. This conflict has radically transformed consumer perceptions of fair prices for energy, grain, medicines and basic goods. In the context of destabilised supply chains and global inflationary pressure, not only material costs but also symbolic value has gained importance as a marker of support, solidarity or moral stance. Behavioural economics has recorded a shift from conventional price elasticity to price ethics, with consumers in certain regions consciously choosing more expensive products based on their origin or impact on the geopolitical situation. Such phenomena require a rethinking of established models of international pricing, in particular by taking into account the emotional consequences of war, collective trauma and the effect of moral signalling projected through pricing policies.

The implications for further research cover several areas. First, empirical testing of integrated models is necessary, considering cultural, demographic and digital diversity. Second, interdisciplinary integration should be strengthened, in particular by involving data from neuroeconomics, emotional price theory and happiness research. Third, there is a need for a normative rethinking of the ethics of pricing in the context of increasing data and power asymmetries between consumers and suppliers, especially in the case of algorithmic personalized pricing systems.

Thus, the discussion of pricing requires not only quantitative models and behavioural theories, but also new paradigms that reflect price as a category of well-being - emotional, moral and social.

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Світовий досвід розвитку франчайзингової діяльності та його застосування в Україні

Ольга Дон, Єлизавета Фрунзе

Purpose. The purpose of the study is to analyze the global development of franchising services and assess their implementation in Ukraine, particularly in the context of post-war economic recovery. **Design / Method / Approach.** The article employs analytical methods, including progression from abstract to concrete, combination of analysis and synthesis, a systemic-structural approach, and the method of cause-and-effect relationships, allowing comprehensive examination of international franchising markets and their adaptation to the Ukrainian business environment. **Findings.** The study demonstrates that franchising significantly contributes to economic growth through rapid business scaling, risk reduction, and knowledge transfer. Comparative analysis shows that franchise systems are most advanced in the United States, while EU countries also show considerable growth. The Ukrainian franchising market remains at an initial stage, constrained by regulatory and infrastructural factors, but shows steady development, particularly in retail, food services, and personal services. The study also highlights the role of franchising in creating employment and fostering investment activity during crises. **Theoretical Implications.** The article examines the essence, types, and theoretical foundations of franchising, including capital involvement and agency theory, demonstrating applicability for structuring franchise relations in Ukraine. **Practical Implications.** The findings support companies in developing effective franchise strategies, identifying promising markets, adapting business models to local cultural and economic conditions, and implementing innovative technologies. **Originality / Value.** The scientific novelty lies in providing evidence-based recommendations for advancing international franchising activities generally, and strengthening the Ukrainian market in particular, including post-conflict recovery. **Research Limitations / Future Research.** Limitations concern implementing global franchising practices in specific sectors of the Ukrainian economy, considering national regulatory frameworks and socio-economic characteristics. **Article Type.** Analytical.

Keywords:

franchising, international business, franchise development, Ukraine, economic growth, post-war recovery

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Мета. Метою дослідження є аналіз світового розвитку франчайзингових послуг та оцінка їх імплементації в Україні, зокрема в умовах післявоєнного відновлення економіки. **Дизайн / Метод / Підхід.** У статті застосовано класичні методи аналізу, включаючи метод від абстрактного до конкретного, поєднання аналізу та синтезу, системно-структурний підхід та метод причинно-наслідкових зв'язків, що забезпечує дослідження динаміки міжнародних ринків франчайзингу та можливостей їх адаптації до українського бізнес-середовища. **Результати.** Дослідження показує, що франчайзинг значно сприяє економічному зростанню через швидке масштабування бізнесу, зниження ризиків та передавання знань. Порівняльний аналіз свідчить, що франчайзингові системи найбільш розвинені в США, країни ЄС демонструють значні темпи зростання, тоді як український ринок перебуває на початковій стадії та обмежений регуляторними й інфраструктурними факторами. Водночас він показує стабільні ознаки розвитку, особливо у сферах торгівлі, громадського харчування та послуг. Дослідження також підкреслює роль франчайзингу у створенні робочих місць та стимулюванні інвестиційної активності у кризові періоди. **Теоретичне значення.** Стаття аналізує сутність, види та теоретичні засади франчайзингу, зокрема модель залучення капіталу та теорію агентства, демонструючи їх застосовність для структурування франчайзингових відносин в Україні. **Практичне значення.** Результати можуть бути використані компаніями для розробки ефективних стратегій розширення франчайзингових мереж, визначення перспективних ринків, адаптації бізнес-моделей до культурних та економічних умов регіонів та впровадження інноваційних технологій у діяльність. **Оригінальність / Цінність.** Наукова новизна полягає у формулюванні рекомендацій щодо подальшого розвитку міжнародної франчайзингової діяльності загалом та українського ринку зокрема, включно з періодом постконфліктного відновлення. **Обмеження дослідження / Майбутні дослідження.** Обмеження пов'язані з імплементацією світового досвіду у конкретних секторах економіки України, з урахуванням національних регуляторних та соціально-економічних особливостей. **Тип статті.** Аналітична.

Ключові слова:

франчайзинг, міжнародний бізнес, розвиток франшизи, Україна, економічне зростання, післявоєнне відновлення

International Experience in the Development of Franchising and Its Application in Ukraine

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Для підприємців та інвесторів однією з найбільш привабливих моделей міжнародного бізнесу на сучасному етапі розвитку світової економіки є міжнародний франчайзинг, який здобув широке поширення завдяки своїм перевагам. Глобальний ринок франчайзингових послуг формує значний і динамічний сегмент економіки, що охоплює тисячі компаній з різних індустрій, які пропонують франчайзингові можливості для підприємців у різних країнах світу. За умов високої конкуренції та обмежених фінансових ресурсів для компаній застосування франчайзингу стало необхідним, оскільки воно дозволяє швидко масштабувати бізнес і забезпечує низку додаткових переваг. Внесок франчайзингу у економічний розвиток та створення робочих місць є суттєвим, що підкреслює його значущість як фактору глобальної економічної активності.

Цілі, завдання та методи

Метою дослідження є аналіз міжнародних франчайзингових послуг та їх імплементація в Україні. Для досягнення поставленої мети визначено наступні наукові завдання: ознайомитися із сутністю франчайзингу, його видами, розглянути переваги та недоліки як інструменту міжнародного бізнесу; проаналізувати міжнародний досвід розвитку ринку франчайзингу; ознайомитися з особливостями нормативно-правової бази регулювання франчайзингових відносин у світі та в Україні; дослідити обсяги і складові світового ринку франчайзингу; проаналізувати розвиток франчайзингового бізнесу для окремих країн, зокрема США та країн ЄС; розглянути динаміку розвитку франчайзингу в Україні; розробити рекомендації дій для покращення стану світового ринку франчайзингових послуг; оцінити перспективи діяльності ринку міжнародних франчайзингових компаній на ринку України у воєнний та повоєнний період. Для вирішення поставлених завдань було використано такі методи: аналізу: метод від абстрактного до конкретного, поєднання аналізу та синтезу, системно-структурний підхід та метод причинно-наслідкових зв'язків.

Теоретичне підґрунтя

На думку більшості українських фахівців, «франчайзинг — це підприємницька діяльність, відповідно до якої на договірних засадах одна сторона передає іншій за винагороду на визначений термін або без зазначення такого: право використання торгової марки; знаку для послуг; фірмового найменування; послуг; технологічного процесу; спеціалізованого обладнання; ноу-хау; комерційної інформації, що охороняється законом; інших, передбачених договором об'єктів права інтелектуальної власності» (Husiev, 2006).

Становлення франчайзингу відбувалося в різних економічних, історичних, соціальних та правових умовах. Розвиток концепції франчайзингу можна умовно поділити на декілька етапів (табл. 1).

Таблиця 1 – Етапи розвитку франчайзингової моделі бізнесу (Zabashtanska, 2016)

Етап	Тривалість	Характеристика
І етап – зародження франчайзингу	До 1851 року	Надання дозволів на продаж товарів на ринках та участь у ярмарках. Системи торговельних гільдій. Власники німецьких та англійських таверн, магазинів розпочали використовувати дистриб'юторські системи «зв'язаних будинків».
ІІ етап – початковий етап становлення сучасних франчайзингових відносин	Середина ХІХ – 40-і рр. ХХ ст.	Налагодження перших франчайзингових систем американськими компаніями Singer, General Motors, Coca-Cola та ін.. Перші АЗС, які почали працювати на основі франчайзингу (початок ХХ ст.).
ІІІ етап – етап розвитку класичного франчайзингу	40-і – кінець 50-х рр. ХХ ст.	Прийняття у США Закону «Про товарні знаки» (1946 р.). Поступово на цій основі склалися певні правила ведення справ власника товарного знака (франчайзера), тобто формувалися відносини франчайзингу.
IV етап – етап інституційного розвитку франчайзингу	Кінець 50-х – 80-і рр. ХХ ст.	Почали укладатись принципово нові види франшиз «бізнес-формат франшизи». Створення Міжнародної асоціації франчайзингу та Європейської асоціації франчайзингу.
V етап – етап поширення франчайзингових мереж у різних галузях економіки	Кінець 80-х рр. 2009 рр.	Франчайзинг діє в більш ніж 75 галузях світового господарства у понад 140 країнах світу. Розпочала свою діяльність Асоціація франчайзингу України (2001 р.).
VI етап – етап інноваційного розвитку франчайзингу	2010 рік і дотепер	У промислово розвинутих країнах діє понад 1 млн фірм, що працюють на основі франчайзингової системи. Франчайзинг розглядається як часткова або модифікаційна інновація, яка дозволяє підприємству-франчайзі отримати додаткові конкурентні переваги над теперішніми і потенційними конкурентами.

Протягом багатьох років для аналізу феномену франчайзингу стало використовуватися все більше теорій, що свідчить про зростання та актуальність цієї сфери економічної діяльності (табл. 2). У сучасній економічній літературі світу пропонують два основних підходи, які пояснюють існування франчайзингу: модель залучення капіталу і теорія агентства. Перший полягає в тому, що франчайзі є ефективним джерелом фінансового капіталу для фірм, які прагнуть розширитися. Незважаючи на те, що це є предметом певних дискусій, аргумент щодо залучення капіталу підтримується концепцією підприємницького партнерства (Kaufmann & Dant, 1999).

Теорія агентства пояснює як вирішується проблема ефективного контролю широко розкидних торговельних точок, які входять до мережі. Франчайзер надаючи франчайзі право на прибуток та сплачуючи неустойку, стимули обох сторін узгоджуються, саме це узгоджує інтереси сторін і дозволяє франчайзі претендувати на частку у праві підприємця. Франчайзі не мають повноцінної свободи у веденні бізнесу, що притаманно будь-якому підприємництву. Будь яке середовище обмежує підприємництво. У франчайзинговій діяльності критично важливою є підтримка основної концепції франчайзера, оскільки їх діяльність має вплив на інвестиції в мережу в цілому. Тим не менш, франчайзі володіють широкими можливостями у розробці унікальних методів просування цієї концепції у своєму регіоні. Для будь-якого бізнесу, який розглядає можливість розширення через франчайзинг, розуміння різних, але взаємозалежних ролей франчайзера та франчайзі є надзвичайно важливим. Франчайзер значною мірою займається контролем процесів ведення та реалізації бізнес франчайзі, а також порядком використанням назви, бренду та бізнес-системи (ACCC, 2023). Франчайзі — це компанія або індивідуальний підприємець, які купують право виступати на ринку від імені франчайзера, використовуючи його бізнес-систему, а також мають можливість навчання та отримання допомоги при створенні бізнесу (Franchise Group, 2024). Зазвичай, франчайзі сплачує франчайзеру початковий внесок, щорічні ліцензійні виплати та постійний відсоток від валового доходу за використання імені та бізнес-моделі франчайзера. Натомість франчайзі отримує доступ до власного бізнес-плану франчайзера та може продавати свої товари чи послуги протягом визначеного періоду в певній географічній зоні. Деякими прикладами популярних сьогодні франшиз є McDonald's, Subway, Domino's Pizza та Bata.

Франчайзинг може мати різні види у веденні бізнесу, залежно від критеріїв класифікації.

За характером діяльності об'єкта

– товарний франчайзинг, за якого франчайзі дозволено продавати його товари або послуги;

– франшиза на продаж готової продукції (виробничий франчайзинг) забезпечує передачу прав на виробництво та збут продукції під торговою маркою франчайзера;

– франшиза на певний вид діяльності (сервісний або бізнес-франчайзинг), окрім передачі права на використання бренду, дозволяє передавати ексклюзивні технології, бізнес-процеси та методику надання певного виду послуг.

За можливостями та намірами франчайзі:

– персональний (індивідуальний) франчайзинг характерний для фізичних осіб, які хочуть створити та керувати єдиним і дуже скромним франчайзинговим бізнесом із продажу товарів або надання послуг безпосередньо вдома або з використанням транспортного засобу;

– бізнес-франчайзинг пов'язаний з сімейним бюджетом, коли члени сім'ї поєднують функції менеджерів і робітників;

– інвестиційний франчайзинг передбачає появу власників нових видів франшиз.

За стратегією розширення франчайзингового бізнесу:

– класичний франчайзинг на опціонних умовах, за якого франчайзі отримує право на відкриття інших франчайзингових підприємств під торговою маркою франчайзера;

– конверсійний франчайзинг передбачає приєднання до системи автономних підприємств зі схожим профілем діяльності під «парасольковим» брендом франчайзера;

– дочірній франчайзинг за формою схожий на конверсійний франчайзинг;

– франчайзинговий договір на управління, коли франчайзі формально стає власником франчайзингового підприємства, але фактично є лише його інвестором (Kyrnytska, 2023).

Таблиця 2 – Теоретична платформа дослідження франчайзингу (Varotto, & Aureliano-Silva, 2017)

I. Теорії, які визначають передумови розвитку франчайзингу		**II. Теорії, які обгрунтовують особливості франчайзингу**	
Теорія глобалізації пояснює закономірності «денаціоналізації економіки», становлення світового ринку, що сприяє міжнародному бізнесу, в тому числі через модель франчайзингу.	II-1. Теорії щодо залучення і використання ресурсів	II-2. Теорії щодо відносин	II-3. Теорії щодо прийняття рішень
Теорія конкуренції пояснює рішення суб'єктів бізнесу про франчайзинг на основі оцінки конкурентних сил сфери діяльності, конкурентних переваг і стратегій.	Теорія дефіциту ресурсів пояснює вибір франчайзингу замість ланцюгів постачання як модель розвитку бізнесу, рішення про початок бізнесу, вибір сфери діяльності й сегменту ринку залежно від наявності ресурсів.	Теорія агентства пояснює закономірності відносин й послаблення розбіжностей сторін, коли один суб'єкт-виконавець представляє відносини іншого-замовника через делегування у прийнятті рішень.	Теорія трансакційних витрат пояснює вагомість витрат на пошук інформації, оцінювання, ведення переговорів і інше.
Теорія «push-pull» факторів пояснює вплив насиченості внутрішнього ринку та розвитку конкуренції («push»-фактори) та можливості розширення масштабів діяльності через вихід на зовнішні ринки, особливо на ринки з «відкладеним попитом» та ринки країн, які розвиваються через модель франчайзингу.	Теорія поглядів на основні ресурси пояснює вибір організаціями тих ресурсів, які є необхідними для здобуття конкурентних переваг на ринку, оцінювання їхньої вартості, поширеності.	Інституційна теорія пояснює важливість дотримання організаціями правил і норм середовища, умов договірних відносин.	Теорія еклектичної парадигми пояснює рішення зниження зовнішніх трансакцій й активізації внутрішніх, якщо їхня вартість буде нижчою, відповідно франчайзер поглибить співробітництво з франчайзі натомість зовнішніх активностей.
Теорії підприємництва, економічна пояснює зв'язок підприємництва й економіки, соціальна — пояснює вплив культури, цінностей, релігії на підприємництво, інноваційна — підтверджує значення творчості та орієнтації на новий результат як рушія розвитку підприємництва, психологічна й біхевіористська — пояснюють вплив оточення на рішення, особливості формування поведінки, мотиваційна —пояснює вплив потреби досягнень на рішення підприємницької діяльності, лідерська — пояснює внутрішні здібності людини бути лідером.	Теорія ресурсної залежності доводить потребу співробітництва організації з іншими організаціями для отримання доступу до ресурсів.	Теорія сигналів пояснює особливості передачі інформації про організацію та її інтерпретації.	Теорія підприємницької орієнтації пояснює бачення керівників організації щодо її розвитку як бізнес-структури, здатності виробляти новий продукт.
Теорія мережевих структур пояснює закономірності неперервного розширення структур та можливості за рахунок цього формувати соціальний капітал.	Теорія права власності пояснює доступ до організацій до ресурсів через систему контрактів, які формують структуру власності.	Теорія зацікавлених сторін пояснює прийняття рішень про укладання договору франчайзингу.	

Кожен вид франчайзингу має як переваги, так і недоліки. Для франчайзі переваги включають доступ до перевіреної бізнес-моделі, маркетингової та рекламної підтримки, а також допомогу на початковому етапі. Недоліки включають високі вступні внески, регулярні платежі роялті, обмеження в управлінні та виборі постачальників. З іншого боку, франчайзер отримує можливість розширити свій бізнес без значних витрат, забезпечуючи додатковий дохід від спільної діяльності, можливість відкрити додаткові філіали та гарантію прибутковості. Проте, франчайзер також має враховувати потенційні недоліки, такі як ризик втрати контролю над брендом, обов'язок підтримки франчайзі, загрозу пошкодження репутації від негативних відгуків, а також необхідність дотримання стандартів мережі. Наразі існують організації метою яких є підтримка та розвиток франчайзингового бізнесу – Міжнародні франчайзингові співтовариства, такі як Міжнародна франчайзингова рада, Європейська федерація франчайзингу, Міжнародна асоціація франчайзингу та Міжнародна франчайзингова мережа. Вони є своєрідною опорою у питаннях пов'язаних з законодавством, бізнес-плануванням, фінансами, маркетингом, технологіями та інноваціями. (Fran Team, 2021).

Міжнародні франчайзингові співтовариства забезпечують пошук франчайзі та поширення необхідного досвіду для успішного розвитку світової франчайзингової діяльності, організовуючи різноманітні заходи, одними з яких є виставки франчайзингу. Саме міжнародні франчайзингові виставки основним інструментом для розширення франчайзингових мереж, так як вони надають можливість зустрічі франчайзера та потенційного франчайзі в одному місці, сприяючи обміну інформацією щодо власних продуктів та послуг (World Franchise Council, 2025). Правове регулювання договорів франчайзингу здійснюється на основі національних правових систем країн світу, зокрема в європейських країнах було розроблено й запроваджено «Кодекс етики франчайзингу» та закон «Модель франчайзингу» (Moniak, 2023). На рівні штатів у Сполучених Штатах існує законодавство, яке регулює франчайзинг приблизно у 18 штатах, натомість в австралійських штатах Південна Австралія та Західна Австралія тривають дебати щодо необхідності подібного законодавства (Spencer, 2013). Франчайзингові договори поступово набирають актуальності в Україні, про що свідчать судова і ділова практика за останні роки, але є проблеми через прогалини у законодавчій базі, так як в країні відсутній відповідний нормативно-правовий акт. В Україні ці договори називаються «комерційною концесією».

Результати

Популярність франчайзингу в світі у XXI ст. швидко зростає. Відповідно інформації світового лідера у сфері зв'язку Franchise Direct, за останні роки було зафіксовано збільшення кількості франчайзі (загалом на 0,32 млн. осіб) та франчайзерів (загалом на 3,7 тис. осіб) на глобальному ринку, що безпосередньо сприяло зменшенню після пандемічного рівня безробіття та зростанню світового обсягу ВВП (Franchise Direct, 2025) (табл. 3, рис. 1).

Таблиця 3 – Характеристика розвитку франчайзингових мереж в світі у 2020–2024 роки (International Franchise Association, 2024)

Показники	2020	2021	2022	2023	2024
Кількість закладів, од.	753770	774965	788914	806270	821589
Зміна до попереднього року, %	-2,6	2,8	1,8	2,2	1,9
Кількість працівників, осіб	7532305	8192600	8421799	8665517	8886555
Зміна до попереднього року, %	-11,4	8,8	2,8	2,9	2,6
Виторг, млрд доларів	677,2	787,7	823,7	858,5	893,9
Зміна до попереднього року, %	-14,7	16,3	4,6	4,2	4,1

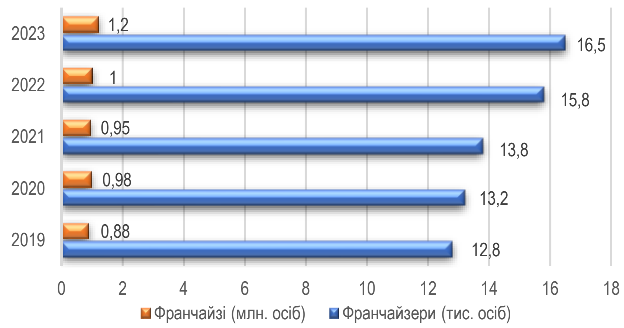

Рисунок 1 – Динаміка розвитку світового ринку франчайзингу (Franchise Direct, 2025)

На світовій арені саме ринки США та країн Європи характеризуються як одні з найуспішніших у сфері франчайзингового бізнесу. Роль франчайзингової діяльності в Європі зростає з кожним роком, оскільки на базі єдиного європейського ринку країни-учасниці отримали значні переваги, пов'язані з інтенсифікацією міжнародного виробництва та просуванням малих і великих компаній. Якщо проаналізувати провідні галузі європейської економіки, що використовують франчайзинг, то їхні результати виглядають таким чином: з великим відривом переважає галузь швидкого харчування (55%), на другій позиції — оренда та продаж нерухомості з часткою 18% ринку, третю позицію зайняла роздрібна торгівля з часткою 14%, сфера послуг опинилася на четвертій сходинці (13%) (рис. 2).

Рисунок 2 – Галузева структура франчайзингової діяльності в ЄС у 2022 році (Nycz-Wojtan, 2023)

На сьогодні Сполучені Штати залишаються лідером у сфері франчайзингу на глобальному рівні. Міжнародна асоціація франчайзингу підрахувала, що у 2023 році в країні працювало 806 тис. франчайзингових компаній, які забезпечували робочі місця для понад 8,4 млн. ос. (ACCC, 2023). Франчайзинг став надважливою стратегією для розширення і зростання бізнесу, створення робочих місць та економічного розвитку як у США, так і на світових ринках (Preble & Hoffman, 1995).

Галузеві пріоритети франчайзингової діяльності в економіці США власне висвітлюють ті сектори бізнесу, які наразі домінують у роботі франчайзингових мереж. Лідерами ринку франчайзингу США є: 20% займає категорія ресторанів швидкого обслуговування, 18% — роздрібна торгівля. Значну питому вагу займають бізнес-послуги (16%), послуги для індивідуальних клієнтів і гастрономія відповідно по 13%, трохи меншу частку автомобілебудування — 5%, посередництва у нерухомості — 4% (рис. 3).

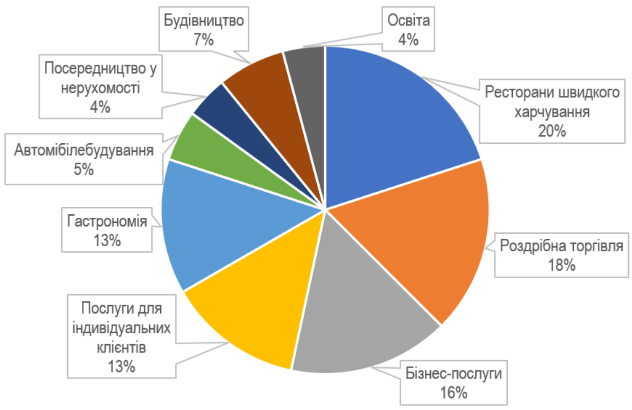

Рисунок 3 – Галузева структура франчайзингової діяльності в США у 2022 році (Nycz-Wojtan, 2023)

У 2024 році франчайзингова галузь у Сполучених Штатах переживала період зростання, оскільки вона адаптувалася до економічних коливань.

В цілому, як американський так і європейський досвід у галузі франчайзингу демонструють його успішність і значний вплив на розвиток міжнародного бізнесу, створення нових робочих місць та забезпечення стійкого економічного розвитку.

SWOT-аналіз є важливим інструментом підтримки прийняття рішень і призначений виявити основні аспекти розвитку світового франчайзингового ринку, розглядаючи його сильні і слабку сторони, можливості та загрози (табл. 4).

Таблиця 4 – SWOT-аналіз розвитку світового франчайзингового ринку (M. Salar & O. Salar, 2014)

Сильні сторони (Strengths)	Слабкі сторони (Weaknesses)
Глобалізація, доступ до нових ринків	Висока вартість
Впізнаваність бренду	Початкові витрати
Менший ризик невдачі	Поточні витрати
Легкість у пошуку фінансової підтримки	Залежність від бренду
Проста система і готова клієнтська база	Суворість правил
Можливості (Opportunities)	**Загрози (Threats)**
Розширення на нові ринки	Висока конкуренція
	Занепад брендингу на ринку
	Економічні кризи

Стосовно українського ринку франчайзингу, то він розпочав своє формування завдяки лібералізації соціально-економічного життя та сфери взаємодії із закордонними партнерами із середини 90-х років XX ст . Функціонування іноземних франчайзерів на території України дає можливість перейняти успішний досвід ведення бізнесу на основі франчайзинг, достатній для більш широкого розвитку його договірної системи.

У 2021 році в Україні функціонувало 592 франчайзингові компанії. Як бачимо з рис. 4, загалом, за період 2010–2015 років кількість франчайзерів збільшилася на 206 од., а середньорічні темпи зростання становили 15%. З 2015 до 2017 року спостерігалося скорочення кількості франчайзингових підприємств на 36%. Поступово відновлювався ринок починаючи з 2018 року, в цей період середньорічний темп зростання склав приблизно 13%. Загалом можна стверджувати, що кількість франчайзингових компаній, які хочуть і надалі розвиватися, до 2022 року стабільно зростала (рис. 4).

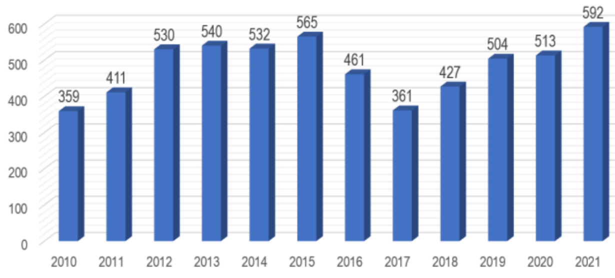

Рисунок 4 – Динаміка кількості франчайзерів в Україні, од. (Franchise Group, 2023)

Перші позиції за популярністю в Україні зберігають франшизи у сфері громадського харчування. У 2023 році вони становили понад 80% усіх проданих українських франшиз. Пояснення просте: вони більш зрозумілі для потенційного партнера, швидко окуповуються та мають широкий вибір різних умов співпраці.

Найбільш популярні франшизи України у 2024 році у сфері громадського харчування: мережа ресторанів грузинської кухні Джигіт, найбільша мережа піцерій в Україні Pizza Celentano Ristorante, львівський концепт мережі пекарень швидкого харчування Lviv Croissants, мережа ресторанів японської та італійської кухні Mafia, одна з найбільших мереж кав'ярень в Україні Aroma Kava (табл. 5).

Таблиця 5 – Найбільш популярні франшизи України у сфері громадського харчування (InVenture, 2025)

Назва	Характеристика
Джигіт	Мережа ресторанів грузинської кухні у форматі Fast-Casual. Обсяг інвестицій — від 30 000$. Вступний внесок – від 8 000$ до 15 000$ в залежності від формату ресторану. Роялті — 3%. Період окупності становить від 9 до 12 місяців.
Pizza Celentano Ristorante	Перша та найбільша мережа піцерій в Україні. Паушальний внесок — від 10 000$ до 20 000$. Обсяг інвестицій становить від 60 000$ до 180 000$, залежно від площі ресторану. Термін окупності — від 12 місяців.
Lviv Croissants	Львівський концепт мережі пекарень швидкого харчування. Обсяг інвестицій становить від 30 000$ до 70 000$, вступний внесок — 10 000$. Розмір роялті — 3% від виторгу. Термін окупності інвестицій — від 12 до 24 місяців.
Mafia	Мережа ресторанів японської та італійської кухні. Вступний внесок — 9 000 євро. Обсяг інвестицій становить від €600/м2, а розмір роялті у перший рік роботи закладу — 3,5% від обороту (далі розмір роялті збільшується до 5% від обороту). Маркетинговий платіж — 2% від продажу. Термін окупності — від 18 місяців.
Aroma Kava	Одна з найбільших мереж кав'ярень в Україні. Залежно від розміру закладу обсяг інвестицій може становити від 250 000 до 850 000 гривень. Сума паушального внеску — 75 тисяч гривень. Термін окупності — від 6 місяців. Розмір роялті — 2% від обороту.

Найбільш популярні франшизи України у сфері послуг: компанія, що займається доставкою поштових відправлень та вантажів Нова пошта, франшиза медичних лабораторій ДІЛА, професійна мережа хостелів нового покоління Dream Hostel, мультиформатна мережа агентств Соната, одна з найбільших туристичних компаній Tez Tour (табл. 6).

Таблиця 6 – Найбільш популярні франшизи України у сфері послуг (InVenture, 2025)

Назва	Характеристика
Нова пошта	Компанія, що займається доставкою поштових відправлень та вантажів в Україні та у світі. Сума інвестицій — від 50 000 до 200 000 гривень. Роялті — 0,5% від обороту. Паушальний внесок відсутній. Термін окупності — від 8 місяців.
ДІЛА	Франшиза медичних лабораторій з 25-річним досвідом. Перша серед українських лабораторій збудувала систему управління якістю (TQM) лабораторних послуг, що відповідає міжнародним та світовим стандартам. Інвестиції на запуск від $18 000. Період окупності 14 місяців. Необхідна площа приміщення: 35-50 м². Чистий прибуток: $2 000/міс., після виходу на 100% завантаження франчайзингової точки.
Dream Hostel	Професійна мережа хостелів нового покоління. Залежно від розміру хостелу, обсяг інвестицій може становити від 200 000 до 2 500 000 гривень. Вступний внесок — від 50 000 до 200 000 гривень. Період окупності — від 9 до 30 місяців.
Соната	Мультиформатна мережа агентств, що надає широкий спектр послуг, пов'язаних із закордоном: працевлаштування, стажування за кордоном, візова підтримка, туристичні послуги. Обсяг інвестицій — від 1000$ до 4000$. Вступний внесок — від 600 до 800 доларів. Термін окупності — від 6 місяців.
Tez Tour	Одна з найбільших туристичних компаній. Вступний внесок для Києва та Дніпра становить 70 000 гривень, для Одеси, Харкова, Запоріжжя та Львова — 60 000 гривень, для решти міст — 50 000 гривень. Роялті — 1% від обороту. Обсяг інвестицій залежить від розміру франчайзингової точки. Термін окупності — від 12 до 24 місяців.

Широко використовується франчайзинг і в сфері торгівлі. Найбільш популярні франшизи України у 2024 році у сфері торгівлі: одна із найбільших в Україні мереж супермаркетів Novus, найбільша мережа магазинів розливного пива ПивоБанк, мережа фірмових магазинів одягу та взуття Columbia, мережа магазинів домашніх напівфабрикатів Галя Балувана, мережа спеціалізованих сирних магазинів Сирне королівство (табл. 7).

Таблиця 7 – Найбільш популярні франшизи України у сфері торгівлі (InVenture, 2025)

Назва	Характеристика
Novus	Одна із найбільших в Україні мереж супермаркетів. Сума інвестицій може становити від 40 000$ до 1000 000$, залежно від формату супермаркету. Роялті — 1% від товарообігу, рекламні відрахування — 1% від виторгу. Термін окупності — від 18 до 36 місяців.
ПивоБанк	Найбільша мережа магазинів розливного пива. Паушальний внесок — від 5 000$. Сума інвестицій — від 12 000$. Роялті — 3% від обороту. Період окупності — від 14 до 18 місяців.
Columbia	Мережа фірмових магазинів одягу та взуття для активного відпочинку американського бренду. Розмір інвестицій — від 25 000$. Термін окупності — від 12 до 18 місяців. Вступного внеску немає.
Галя Балувана	Мережа магазинів домашніх напівфабрикатів. Паушальний внесок — 9 000$. Роялті — 2000 гривень на місяць із однієї франчайзингової точки. Обсяг інвестицій — від 30 000$ до 40 000$ для магазину площею 60 кв. м. Термін окупності — від 5 місяців.
Сирне королівство	Мережа спеціалізованих сирних магазинів європейського формату. Паушальний внесок — 10 000€. Обсяг інвестицій — від 23 000€. Роялті — 4%. Термін окупності — від 12 до 18 місяців.

Незважаючи на напружену економічну ситуацію в Україні, розвиток франчайзингового бізнесу не припиняється, оскільки велика кількість фанчайзерів все ж змогли адаптуватися до нових і більш складних умов.

Рекомендації

Щоб успішно орієнтуватися в майбутньому розвитку франчайзингу, бренди повинні прийняти ефективні стратегії. Визначення та оцінка потенційних можливостей для франчайзингової діяльності є дуже важливими. Це передбачає проведення ретельного дослідження ринку, щоб зрозуміти запити споживачів і конкурентне середовище.

Стратегії розвитку франшизи повинні включати в себе фокус на масштабованість. Масштабованість має вирішальне значення для успіху франшизи, дозволяючи брендам розширювати своє охоплення, зберігаючи при цьому операційну ефективність. Наприклад, франшиза повинна гарантувати, що її бізнес-модель може бути відтворена в різних місцях без втрати якості.

Для подальшого розвитку міжнародної франчайзингової діяльності загалом і в Україні, зокрема, необхідно проводити такі дії:

– аналізувати ринки країн, проводити постійні ознайомлення з уподобаннями та потребами споживачів;
– адаптувати діяльності компанії до культурних особливостей цільового регіону;
– запроваджувати сучасні наукові та інноваційні технології;
– здійснювати інвестиції у найбільш фінансово привабливі та перспективні сектори економіки.

У зв'язку з поточною ситуацією в Україні, важливість франчайзингу набирає обертів особливо як знаряддя для відновлення української економіки та розвитку бізнес-діяльності. Повномасштабне розгортання бойових дій у 2022 році майже на всій території України змусило всю країну адаптуватися до життя в умовах воєнного часу. Через війну український бізнес почав масово відкриватися в Європі, створюючи ринок для українських франшиз. Зокрема, консалтингова компанія Franchise Group, яка займається просуванням франчайзингових послуг, щодня отримує все більше запитів на запуск франшиз за кордоном, ніж будь-коли. Отже, в останні роки національний ринок франчайзингу повільно, але стабільно розвивається. Держава здійснила низку комплексних змін у законодавстві та державних програмах, щоб посилити підтримку економіки та розвитку українського бізнесу, що надалі сприятиме розширенню франчайзингової діяльності.

Висновки

Франчайзинг є стратегічним альянсом між двома сторонами: франчайзером, який володіє бізнесом, та франчайзі, що набуває право на продаж продуктів і послуг франчайзера. Ця форма бізнесу продовжує активно розвиватися та поширюватися у міжнародному масштабі. Лідерами у сфері франчайзингового бізнесу є країни з високим рівнем економічного розвитку. Зокрема, досвід США та країн ЄС демонструє, що франчайзинг виступає ефективною моделлю розширення існуючого бізнесу.

Франчайзингова модель бізнесу є привабливою і для вітчизняних підприємців. Найбільш активно вона розвивається у сферах громадського харчування, торгівлі та послуг. В Україні більшість учасників ринку франчайзингу стикаються переважно з правовими труднощами, проте, незважаючи на ці обмеження, франчайзинговий бізнес демонструє стрімке зростання. Сьогодні франчайзинг набуває значення як інструмент відновлення української економіки та розвитку бізнес-діяльності.

Франчайзинг вже давно розглядається як одна з найбільш зручних і ефективних моделей розвитку малого та середнього бізнесу. Наявність готового бренду дозволяє уникнути значних витрат на просування, а початківець-підприємець працює під перевіреним форматом, що мінімізує ризики.

Для стимулювання розвитку міжнародного франчайзингу необхідно створити сприятливі умови: здійснювати моніторинг ринку та вивчати уподобання і потреби споживачів; адаптувати діяльність компанії до культурних особливостей цільового регіону; впроваджувати сучасні наукові та інноваційні технології; інвестувати у найбільш перспективні сектори економіки.

Подальші дослідження мають бути спрямовані на розвиток малого та середнього бізнесу у постконфліктних регіонах, удосконалення механізмів адаптації франчайзингових мереж до економічних трансформацій, а також на оцінку ролі державної політики у стимулюванні інвестиційних процесів та розвитку національної економіки.

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Green Economy Potential in the Organization of Turkic States: Comparison of Economic Indicators

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Purpose. The main objective of this study is to assess the potential of the green economy to promote economic growth and development in the member states of the Organization of Turkic States (OTS). The object of the study is the OTS countries, and the subject is the analysis of green economy potential and comparison of relevant economic indicators. **Design / Method / Approach**. The research draws on data from international sources, including UNECE, TheGlobalEconomy.com, national statistics of Azerbaijan, and other open datasets. A systems approach, logical generalization, comparative analysis, and cause-and-effect reasoning were applied. **Findings**. The study addresses: (1) the green economy as a category of modern mutually beneficial development; (2) comparison of economic growth and green economy indicators in OTS countries; (3) green economy potential in Azerbaijan; and (4) the experience of green economy implementation in OTS states. The authors identify key challenges and propose recommendations for improving the implementation of green economy objectives. **Theoretical Implications**. All OTS countries show interest in green economy development by attracting investment and creating favorable conditions in industrial zones, agriculture, transport, and tourism. **Practical Implications**. Each OTS member has adopted a strategy for greening the economy and is gradually implementing its elements in alignment with national goals. **Originality / Value**. The study introduces a green economy index, identifies barriers to economic growth and sustainable development, and highlights structural shifts in the economy driven by green economy expansion. **Research Limitations / Future Research**. The main limitation is the lack of a complete statistical base. Nonetheless, the study formulates conclusions and proposes measures to address identified issues. **Article Type**. Applied, empirical research paper.

Keywords:

green economy, Organization of Turkic States (OTS), economic growth, comparison of economic indicators, sustainable development, investment in green economy

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Мета. Головною метою цього дослідження є оцінка потенціалу зеленої економіки для сприяння економічному зростанню та розвитку країн-членів Організації тюркських держав (ОТД). Об'єктом дослідження є країни ОТД, предметом – аналіз потенціалу зеленої економіки та порівняння відповідних економічних показників. **Дизайн / Метод / Підхід**. Дослідження базується на даних міжнародних джерел, зокрема UNECE, TheGlobalEconomy.com, національної статистики Азербайджану та інших відкритих наборів даних. Застосовано системний підхід, логічне узагальнення, порівняльний аналіз та причинно-наслідкове мислення. **Результати**. У дослідженні розглянуто: (1) зелену економіку як категорію сучасного взаємовигідного розвитку; (2) порівняння показників економічного зростання та зеленої економіки в країнах ОТД; (3) потенціал зеленої економіки в Азербайджані; (4) досвід впровадження зеленої економіки в країнах ОТД. Виявлено ключові проблеми та запропоновано рекомендації для покращення реалізації завдань зеленої економіки. **Теоретичне значення**. Усі країни ОТД демонструють зацікавленість у розвитку зеленої економіки шляхом залучення інвестицій і створення сприятливих умов у промислових зонах, сільському господарстві, транспорті та туризмі. **Практичне значення**. Кожна країна-учасниця ОТД ухвалила стратегію озеленення економіки і поступово впроваджує її елементи відповідно до національних цілей. **Оригінальність / Цінність**. У дослідженні введено індекс зеленої економіки, визначено бар'єри економічного зростання і сталого розвитку, а також наголошено на структурних змінах в економіці, викликаних розширенням зеленої економіки. **Обмеження дослідження / Майбутні дослідження**. Основним обмеженням є відсутність повної статистичної бази. Втім, зроблено висновки і запропоновано заходи для розв'язання виявлених проблем. **Тип статті**. Прикладне емпіричне дослідження.

Ключові слова:

зелена економіка, Організація тюркських держав (ОТД), економічне зростання, порівняння економічних показників, Сталий розвиток, інвестиції у зелену економіку

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A green economy promotes balanced economic development, considering the use of all key factors: ecology; natural, labor, financial, and production resources; productive forces; production relations; and the interaction between the state and private sector partnerships. The green economy also contributes to improving coordination among all participants and enhancing the well-being of the population. It not only addresses the challenges of economic development but also emphasizes environmental and socio-economic dimensions, thereby ensuring economic growth alongside ecological balance. The OTS countries possess rich natural resources, an adequate level of population education, scientific and production potential, a stable inflow of investments, and a strategic interest in diversification and occupying niches for new goods and services in both domestic and international markets (Table 1).

Table 1 - Commodity Structure of Foreign Trade with the Countries of the Turkic World in 2021, % of total (Gasimli, 2023, p. 285)

	Azerbaijan		Kazakhstan		Kyrgyzstan		Turkey		Total	
	export	import	export	import	export	import	export	import	export	import
Overall	100	100	100	100	100	100	100	100	100	100
Food products and live animals	13.7	12.3	17.5	34.4	15.3	9.8	1.5	3.1	9.6	19.0
Beverage and tobacco	0.0	0.6	1.2	0.2	0.6	0.6	0.0	0.0	0.5	0.1
Non-food raw materials, except fuel	4.9	29.8	4.8	15.9	1.0	8.9	3.4	1.5	3.4	9.1
Mineral fuels, lubricating oils and similar materials	0.4	18.4	0.5	10.5	1.2	27.3	0.6	0.4	0.7	18.6
Animal and vegetable oils, fats and waxes	0.0	0.2	0.0	2.9	0.0	0.0	0.0	0.0	0.0	1.5
Chemical and similar products	1.6	18.6	8.1	2.4	6.9	1.3	7.5	17.5	8.5	7.7
Industrial goods	45.7	17.3	15.0	25.3	33.9	41.5	81.4	16.7	47.5	19.9
Machinery and transport equipment	26.5	0.7	34.6	6.2	4.2	6.8	2.6	47.8	13.0	18.7
Various finished products	4.1	0.3	5.1	0.5	24.1	1.1	0.2	9.3	8.6	3.3
Other goods	0.0	0.0	0.0	0.2	0.3	0.0	0.0	0.0	0.1	0.1
Services	3.2	1..9	13.1	1..4	2.4	2.8	2.8	3.5	8.2	2.1

The participation of these countries in international organizations, international scientific and technical and technological cooperation, in exhibitions and large interstate projects is based on a comprehensive study of not only legal and economic acts, but also in the development of ICT and telecommunications, which increases the importance of the "green economy" (Accenture & United Nations Global Compact, 2018).

Green Economy as a Category of Modern Mutually Beneficial Economy

The Green Economy Concept, which first introduced a serious critical approach to the value of money and material wealth in the concept of human well-being after the 1960s and defined as an economic foundation, was held in Rio de Janeiro on June 20-22, 2012 and Rio+ 20 has become one of the most topical issues since the United Nations Conference on Sustainable Development (UN-DESA, 2012). Twenty years after the 1992 Rio Conference on Sustainable Development, the concept of "green economy" became the focus of the UN Conference on Environment and Development (UNEP, 2012).

The United Nations Environment Program (UNEP) sees the green economy as a growth strategy that addresses environmental risks and environmental challenges, as well as increasing human well-being and social equality. More specifically, the green economy can be seen as an approach aimed at reducing greenhouse gas emissions, resource efficiency and social development. In a model that can be called a green economy, income and employment can be achieved through reducing pollution and carbon emissions, improving energy and resource efficiency, conserving and enriching biodiversity, and public and private sector investments.

Given that the common future of mankind depends on the cooperation of states, the green economy, which requires a common understanding and common vision, includes the creation of a policy of environmentally friendly growth and development. In order to protect the common future, it must be borne in mind that consensus in the field of environmental and sustainable development must not remain in theory and must be implemented. Accordingly, in October 2012, the United Nations Development Program (UNDP) seminar on "Fiscal Policy in an Inclusive Green Economy" focused on three key areas: environmental protection taxes and duties, energy subsidy revision, and financial reform.

The United Nations Development Program supports the support of investments in the green economy through public spending and political and administrative reforms. In addition, the protection and development of natural assets, which are the main source of capital and are of great value, is extremely important for people who make a living from natural resources (Burkhard & Müller, 2008; UNEP, 2011b).

The term green economy was first mentioned in the Green Economy Plan Report published in 1989 by the London Center for Environment and Economics (UNEP, 2011b). There is no single definition of a green economy, but various international organizations have provided explanations for this concept (GEC, 2019; Duijvestein, 2002; Jabareen, 2006).

UN. A model of economic growth that helps to reduce poverty while maintaining a sustainable economy, ensures the sustainability of a healthy ecosystem, supports sustainability in the process of production and consumption, contributes to the creation of new employment opportunities, and enhances social welfare.

UNEP. It is about ensuring human well-being and social well-being while reducing environmental risks and shortages. In addition, the green economy includes issues such as efficient use of resources, reducing carbon emissions, and improving the social situation.

UNESCAP. Ensuring economic growth by focusing on the environment, reducing carbon emissions, and addressing social issues.

OECD. An environmentally friendly green economy is about achieving economic growth and development after ensuring the long-term use of natural resources based on human well-being. In addition, the green economy must support growth and contribute to investment and innovation to increase economic opportunities to achieve sustainable development.

WB. It is a concept of economic growth that reduces the conditions that cause environmental problems, uses resources efficiently, does not harm living things in nature, and does not slow down development.

G20 Platform. A model of sustainable development, the Green Economy is a growth model that allows old technologies in various sectors to be replaced by new technologies that are less harmful to the environment and increase energy efficiency.

"Green" and "greening" (Table 2) are used for sustainability and related issues where energy and resource efficiency are central elements of green economy. The deterioration of the ecological situation in Europe due to air pollution and water supply led to the study of the ecological situation in the industrial cities of Europe. In the 1980s, the reports The Limits to Growth introduced the idea of sustainable economic growth; Our Common Future demonstrated it was possible to reconcile economic growth, environmental preservation, and social development; and the New Urbanism Movement advocated ways to limit dispersed urban expansion of cities by using more environmentally friendly urban design practices such as walkable neighborhoods, mixed land use, and transit-oriented developments (TODs) (Brilhante & Klaas, 2018; Duijvestein, 2002; Jabareen, 2006).

The green economy is a new and developed mechanism based on an innovative system of economic activities that enhances social welfare and ensures competitive but responsible business growth. The green economy, which stimulates transformation, encourages and facilitates progress towards the three pillars of sustainable development. More than 60 countries around the world are moving towards a green economy, and many want to achieve their ambitions in the next 10 years. Leading governments in this transition are breaking the traditional line of thinking that there is an inevitable compromise between economic progress and environmental sustainability, and instead demonstrate significant opportunities for investment, growth and security (Environmental Management Group, 2019; Kuloğlu & Öncel, 2015; Tjallingii, 1996).

Table 2 - Difference between brown and green economy (based on the analysis of existing literature on brown and green economy)

Brown economy	Greening	Green economy
Traditional economic growth	Economy growth's planning	Separating economic growth on natural resource using
Non-renewable energy sources	Control on energy sources' using	Renewable energy sources
Intensive consumption of natural resources	Optimization of natural resource using	Energy efficiency
Destruction of biodiversity	Biodiversity controlling	Biodiversity protection
Unlimited consumption (over consumption)		Sustainable consumption
Lack of Corporate Social Responsibility of Businesses and Investors	State monitoring, marketing regulation and financial controlling	Corporate Social Responsibility of Businesses and Investors

In the long run, investing in green economy policies will result in faster economic growth. A green economy will overcome challenges such as energy shocks, water scarcity and ecosystem loss, and investments will be directed more to employment and agricultural productivity, which will lead Green economy and Green Finance to poverty reduction (Maran & Nedelea, 2017). Mechanisms that provide a green economy, such as renewable energy, a green business and technology-friendly environment, and the training of a skilled and agile workforce, are also the driving force and outcome of the transition. The creation of low, medium and highly skilled jobs is just one of the short-term benefits of the transition to a green economy. Other opportunities for governments include improving the health and well-being of the population, leading to higher productivity and reducing healthcare costs. The transition to a green economy requires special conditions. These favorable conditions include the government of national economies, domestic and foreign policy, subsidies and support, as well as international markets and legal infrastructure, trade and technical assistance to developing countries. Steps are now being taken through the green economy against the dominant brown economy, which is overly dependent on natural resources, depleting them and degrading the environment. There are two equally important aspects of the transition to a green economy: greening the brown economy and green growth. Any brown economic sector can be greened through the application of clean, efficient and innovative technologies. Green growth should be stimulated by investing in new green industries.

If ecology means the study of home (environment), then economics is the science of housekeeping. The economy of countries has always depended primarily on natural resources, their quality and availability (UNDESA, 2012). As Mamedov notes, the deep connection between economics and ecology became apparent when the reverse impact of the changes made by people on man and his economy became obvious (Mamedov, 2003). J.-B. Lamarck, E. Reclus in 19th century, V. Vernadsky at the beginning of 20th century in their works pointed out the determining role of the environment on the economy. K. Marx studied the connection between capital and labor, but did not pay attention to natural resources, their potential and possibilities. With any economic activity, natural resources are depleted, and the effect of environmental pollution appears. Since the economy itself is a multifactorial process, it is studied using complex multidisciplinary methods that take into account the political and social aspects of economic development within the framework of natural and social sciences. W. Jevons and L. Walras, as well as T. Veblen and A. Salleh, considered some aspects of the green economy from both the marginalist and institutionalist perspectives.

The goal of any national socio-economic development strategy should not be limited to growth and development, but must also address global social challenges. GDP per capita reflects how much is spent on health care, but it does not capture the outcomes of these expenditures, that is, the actual state of public health, which is better indicated by average life expectancy. GDP may increase, yet the overall effectiveness of the health care system can decline, and the health of the population may deteriorate. Similarly, relying solely on average GDP per capita provides an incomplete picture of well-being. Therefore, it is crucial not only to correctly use green economy indicators but also to plan appropriate strategic and tactical actions (Yuzbashiyev, 2010). Implementing a green economy policy aims to ensure sustainable growth and development of the national economy, enhance security, address social challenges, and prioritize solutions to environmental and climate change issues.

Economic growth and green economy indicators — comparison of OTS countries. In the theory of economic growth, quantitative indicators are more often addressed, and then qualitative components. In the green economy, the main indicator has become the qualitative component of economic growth and development. The quantitative criterion of growth is ensuring sustainable rates of GDP growth. Qualitative characteristics of growth are factors of economic growth that ensure the growth of the people's well-being, reduction of differentiation in the standard of living of the population, reduction of mortality, increase in life expectancy, improvement of the environment, increase in competitiveness, etc. (Yuzbashiyeva, 2010). Many countries have differences in the structure of their national economies, and there is uneven development among sectors and branches of economy, in regional development, and among enterprises and the working population. These problems increase the importance of coordination to solve future problems. It should be noted that sustainable development means meeting current needs without compromising the needs of future generations.

This is achieved through balanced socio-economic-ecological growth and development, which creates the foundations for sustainability and the transition to a "green" economy, the essence of which is to improve people's well-being, social equality and reduce the impact of environmental risks in conditions of uncertainty. Innovative and inclusive growth, the use of "green" GDP, in which the environmental component is strengthened. If the indicator of green economy GDP is negative, this demonstrates a low level of use of energy from renewable sources, low quality of ecology, underdevelopment of ecotourism, a small number of protected natural resources in the territory of the state (Abasova, 2015; Abasova et al., 2020). As is known, the indicators of economic growth are the growth of GDP, the growth rate of GDP, and the growth rate of production. The main indicators of economic development are: sectoral structure, GDP per capita, production of basic products per capita, the standard and quality of life of people. Let's consider some of them (Table 3).

Table 3 - Economic indicators by OTS countries in 2023 (Humanitarian Portal, 2025; TheGlobalEconomy.com, 2024; UNECE, 2024)

	GDP, current, billions. $	Number of employed populations, million people	Annual labor productivity		Population size, million people	Current GDP per capita, $ per year	Share of employed population, %, 2023	Share of employed population, %, 2024
			Thousands, $/person	100%				
Turkey	1118.25	31.632	7.63	-	85.326	13105.66	37.1	48/152
Azerbaijan	72.36	4.963	14.58	4.2	10.11	7125.91	49.1	66/31
Kazakhstan	261.42	9.082	28.79	8.3	19.9	13136.68	45.64	65/38
Kyrgyzstan	13.99	2.656	5.27	1.5	7.1	1970.42	37.41	63/47
Uzbekistan	90.89	13.865	6.56	1.9	36.41	2496.29	38.08	54/124
As an observer of the activities of the OTS								
Turkmenistan	59.89	2.120	28.25	8.2	6.52	9185.58	32.52	46/158

As can be seen from the data in Table 3, there is high labor productivity in Kazakhstan (28.79 thousand $/person) among OTS countries. Azerbaijan has low values - 14.58. However, there are no significant differences in the share of the employed population.

Thus, the share of employed population in Turkey is 37.1%, in Azerbaijan - 49.1%, in Turkmenistan (32.52%), in Uzbekistan (38.08%), in Kyrgyzstan (37.41%). All this demonstrates the feasibility of increasing efficiency, productivity and effectiveness. The importance comes from the fact that the significance of environmental issues, uncertainty in global development, the impact of digitalization and artificial intelligence are increasing, which is reflected in the indicators of economic growth and development.

The processes of greening, digitalization and socio-economic development of any country are reflected in the indicators of economic growth and development of the country, which are subject to certain changes (Yuzbashiyeva et al., 2023). These changes have qualitative characteristics, not quantitative ones, as they ensure sustainability, competitiveness, inclusive growth and development of the country. Economic growth leads to an increase in the physical volume of production, an improvement in the quality of final product, and simultaneously affects the standard and quality of life of population, the technological structure and efficiency of production factors (Yuzbashiyeva et al., 2023). It is important to combine the influence of the country's economic, social, technical, technical and ecological development.

The main risks in the country's economic development are (Yuzbashiyeva, 2010): climate and environmental problems, instability, problems from the use of digitalization and artificial intelligence technologies, cybersecurity, lack of information and disinformation, income polarization, local wars, sanctions, inflation, migration, volatility of raw material prices, volatility of industrial production, etc.

All of this is reflected in the formation of GDP (reduction in the volume of expenditure on investment and consumption). Innovative technologies influence the content of work and lead to the disappearance of some professions and the emergence of new ones. Changes may occur in economy structure: in the sphere of employment (growth in the number of jobs associated with the "green" economy); creation of new markets (Abasova et al., 2020) and types of activity; in the investment and innovation sphere; regional development based on the creation of new industries and jobs; growth of social investments in the conditions of competition (Yuzbashiyeva & Abasova, 2022) and the transition to digitalization.

In turn, digitalization leads to inclusive and sustainable growth. This requires optimal distribution of investments between economic sectors, as it ensures the transition to a "green" economy, the application of ESG standards. In the context of decreasing uncompetitiveness of industries and markets, it is necessary to diversify the economy. On the other hand, it is expedient to increase funding for scientific and technical and technological research and development that stimulates economic growth and development. The issues of high-quality economic growth and development create the foundations for sustainability and stability, which determines the green economy (Yuzbashiyeva et al., 2022).

The creative potential of workers in a green economy should be directed towards filling technological gaps through local technological changes. The products produced may be at a lower technological level, but they will fill the gaps in the final consumption sphere (Yuzbashiyeva et al., 2025).

The quality-of-life index consists of 8 indicators: (1) PPİ — purchasing power index; (2) Sİ — safety index; (3) HCİ — health care index; (4) CLİ — cost of living index; (5) PPİR — property price to income ratio; (6) TCTİ — traffic community time index; (7) Pİ — pollution index; (8) Cİ — climate index (Table 4). Data for Kyrgyzstan and Uzbekistan are not available.

As shown by the data in Table 5, Azerbaijan and Kazakhstan occupy average positions on this index (63rd and 72nd place). Safety index in Azerbaijan is higher (68.4) than in Turkey (59.1) and Kazakhstan (54.1). But health care index in Azerbaijan (47.7) is lower than Kazakhstan (60.1) and Turkey (70.7). Cost of living index is either for all OTS countries. The situation in Azerbaijan and Kazakhstan has improved, but there is still much to be done. Azerbaijan Government is doing a lot of work in this direction, which is reflected in this quality-of-life index (increased investment in education, healthcare, solving environmental problems, reducing the complexity of military issues, etc.).

Based on the importance of the current situation, Azerbaijan Government is carrying out certain work to improve the situation and reduce the country's dependence on resources (Abasova, 2015). As a result of the work carried out by the Government of the country, the foundations for increasing sustainability, competitiveness and efficiency have been created in order to complicate the economic structure (Yuzbashiyeva et al., 2024). A foundation has been created that provides conditions for Azerbaijan to become a developed country and is included in the group of countries with an above-average income.

Table 4 – Quality-of-life index in 2024 (Numbeo, 2025)

	Place	Index	PPI	SI	HCI	CLI	PPIR	TCTI	PI	CI
Turkey		123.6	39.3	59.1	70.7	33.8	12.5	44.1	64.7	93.3
Azerbaijan	63	109.8	29.4	68.4	47.7	31.1	14.4	39.1	73.1	91.4
Kazakhstan	72	98.4	36.8	54.1	60.1	33.5	10.4	35.8	73.6	39.8

Note: PPI - purchasing power index; SI - safety index; HCI - health care index; CLI - cost of living index; PPIR – property price of income ratio; TCTI – traffic commute time index; PI - pollution index; CI - climate index.

Table 5 - Indicators of economic development of Azerbaijan (AzStat, 2024; Imanov, 2017)

	2020	2021	2022	2023	2024
GDP, million $	42693.0	54825.4	78807.5	72356.2	74.3 billion $
Volume of raw materials export, million $	13732.6	22208.0	38146.7	33898.6	
GDP, %, environmental protection expenditures	0.33	0.27	0.23	0.29	0.30
Environmental protection costs, million manat/million $	240.6/141.5	246.0/144.7	281.6/165.7	358.57/210.9	376.87/221.7
GDP growth	- 4.3	5.6	4.7	1.1	4.1
"green" GDP, million $	28818.9	32472.7	40495.1	38246.7	
"green" GDP, % of GDP	67.5	59.2	51.4	52.9	
Human Development Index (HDI)	0.756/88	0.745/91	0.750/92	0.760/89	
Environmental Performance Index	46.5/72	-	88.60/104	40.4/121	40.5/121
Cost of living index	33.0	30.9	39.6	31.2	30.9
Health Index	58.87	44.0	32.0	47.1	48.3
Investments in fixed assets, billion $	10.1	9.9	10.5	12.5	
Network Readiness Index	48.76/66	47.56/76	-	-	46.08/75

Note: Economic development indicators were calculated by G. Yuzbashiyeva and I. Yuzbashiyev using the method of K. Imanov (Imanov, 2017).

Opportunities of Green Economy in Azerbaijan

As the President of Azerbaijan Mr. I. Aliyev said at the COP29 meeting (11-22 November 2024): "... we will resolutely advocate for a "green" transition, and we are doing this. But, at the same time, we must be realistic" (Official website of the President of the Republic of Azerbaijan, 2024). The growth of the non-oil sector contributes to the replenishment of the budget, increasing sustainability, efficiency and effectiveness. The quantitative criterion for growth is ensuring sustainable GDP growth rates. All measures taken by the Government of Azerbaijan contribute to the creation of the foundations of a "green economy". The "green" GDP index shows economic growth taking into account environmental pressure (Table 3).

As shown in Table 5, economic indicators are improving. For example, GDP has increased, and its rate was 4.1% in 2024, the human development index and the network readiness index have improved. Not only is there an increase in environmental spending in GDP, but environmental pressure on economic growth is also growing. The European Bank for Reconstruction and Development (EBRD) has assisted in the preparation of an investment program with a total financing volume of US $232 million for the reconstruction and modernization of AzGRES (the country's largest thermal power plant) by providing a loan of US$207 million.

The project includes:

(1) reconstruction of all turbines and boilers and modernization of the control and monitoring system using EBRD funds;

(2) repair of one section of the cooling tower and the water-cooling system;

(3) implementation of environmental, health and labor protection measures.

The use of "green" GDP promotes clarity and comprehensibility in definitions, which creates certain advantages. It should be noted that negative values indicate losses in value rather than profitability. Also, the assessment of environmental component of "green" GDP index is carried out using economic indicators, which simplifies and facilitates the conceptual apparatus (Yuzbashiyeva, 2025).

According to S&P forecasts, the average annual GDP growth of Azerbaijan in 2025-2027 will be 2%. The agency forecasts the nominal volume of Azerbaijan's GDP in 2025 at 127 billion manat (US$75 billion), in 2026 - 132 billion manat (US$78 billion), in 2027 - 137 billion manat (US$81 billion). According to the forecasts of the Azerbaijan government, "GDP growth in 2024 will be 4.2%, in 2025 — 3.5%, in 2026 — 2.8%, in 2027 — 3.8%. S&P believes that the manat exchange rate against the dollar will remain unchanged until 2028.

"We forecast that Azerbaijan will maintain the peg of the manat to the US dollar at 1.7 manat per 1%, supported by regular interventions by the authorities in the foreign exchange market. However, if hydrocarbon prices fall sharply and remain low for a prolonged period, we assume that the authorities will consider adjusting the exchange rate to protect the central bank's foreign exchange reserves from a significant decline" (S&P Global, 2025) the agency notes.

Experience of applying green economy in OTS countries

Azerbaijan

Ecologically sustainable socio-economic system adopted in Azerbaijan in 2003. The state program based on development covers all important environmental aspects. This program includes clean atmosphere, water resources, and land resource saving. In 2004 Azerbaijan government adopted state program on the use of alternative energy sources: using wind energy and the construction of wind power plants. Azerbaijan's industrial cities have been using a variety of methods since the 1960s to prevent emissions. It is also planned to increase the number of metro stations operating to 60 in 2040. The Green Growth Strategy like as branch of Green Economy Concept, was adopted by the Azerbaijan Government of in 2005.

This strategy initially included four priority areas: (i) rational model of production and consumption; (ii) "greening" of enterprises and markets; (iii) sustainable infrastructure; (iv) "green" tax and budget reforms. Later, two more were added to these directions: (v) investments in natural capital; (vi) indicators of environmental efficiency. It will currently support low-carbon production in Azerbaijan, resource-efficient a policy that will ensure the use and transition to a socially inclusive economy performed.

İn 2009 were established "Alternative and Renewable Energy" State Agency for Sources (hereinafter referred to as ABOEMDA) and "Alternativenerji" LLC. Out Household waste as a result of structural reforms and the State Program Combustion Plant, about 10 hydropower plants in the regions, 5 in Khizi city and in Absheron peninsula created a wind power plant, a hybrid power plant in Gobustan, a lot of Heat pumps and solar panels have been installed at facilities located in the regions.

As a result, 65 MW of wind energy with a total installed capacity of 260 MW, 126 MW hydroelectric power, 39 MW biomass and waste, 32 MW solar power plants were built and put into operation. At the same time Sumgayit city Technology Plant and Azguntex solar panels enterprise for solar panels' production was built. Table 6 demonstrates SWOT analysis of green economy implementation in Azerbaijan by S. Abasova.

Table 6 - SWOT analysis of green economy implementation in Azerbaijan (author's own development)

S - Strengths	W - Weaknesses
The presence of 2 artificial satellites in Azerbaijan will create conditions for the development of the ICT sector and meeting the demand for smart technologies in digital campuses.	Weak promotion of smart/green economy concept among the population.
According to EBRD, new types of containers, expansion of the existing fleet and the introduction of more environmentally friendly vehicles will be provided, which will significantly reduce the carbon footprint of municipal services of the Ganja city.	Lack of smart/green urban promotion among preschool and high school students.
The presence of green urban-type housing estates in Azerbaijan (Sumgayit, Mingachevir city experience, Baku boulevard) will stimulate the development of living standards in accordance with health requirements.	Insufficient activity of local authorities and municipalities on environmental propaganda.
	Lack of propaganda among the population on separate waste collection.
O - Opportunities	**T - Threats**
Construction of Sumgayit and Mingachevir cities from scratch and creation of smart modern residential complexes there.	Decrease of water in the basin where the Kura River flows into the Caspian Sea because of construction of modern reclamation systems for arable lands and flooding of the seashore.
Partial application of technologies for the movement of smart traffic lights in cities, water and heat supply, gas supply management, as well as the regulation of public transport on demand by ICT.	Mass felling of trees in Baku for the last 30 years.
Existence of water treatment system for the population created based on German technologies in Baku and Sumgayit.	
Creation of green belts in Baku for more than 100 years.	
European Bank of Reconstruction and Development (EBRD) has allocated 10 million euros for smart waste collection and route optimization systems in Ganja city.	

However, despite this, user knowledge of technology, e-commerce and e-payment systems is limited and trust in such systems is low. While all the problems listed above can be solved through advanced technology and technical solutions, the main obstacle is management. For the successful implementation of the concept of a smart/green city, the population in these cities must cooperate with local authorities and play an active role in making decisions about the fate of the city. Smart/green city concept can't work without the participation of the population and their voice.

One of the main problems in Azerbaijan is the use of a monocentric model in the process of governance and urbanization. Observations of the current situation in Baku show that the management of such a large metropolis in the traditional way is inefficient, and there is a need to resort to new innovative management methods based on digital technologies. There is a great need for digital technology management of traffic congestion, waste and utilities. The weakest sub-sector in which Azerbaijan lags behind many countries is the level of use of knowledge and technology. Although digital systems such as e-government, e-education, e-banking, e-medicine have been created, their comprehensive use of high-speed internet and information technologies is required for their use in accordance with modern standards.

Establishment and effective management of smart/green settlements should establish mechanisms for public relations with municipalities and local authorities, and attention should be paid to increasing the civic role of the population. Bringing municipalities and local communities together can play a key role in building the first stone of a smart economy.

"In recent years, important steps have been taken in Azerbaijan towards the transition to a "green economy". In accordance with the UN Sustainable Development Goals, our country has achieved significant success in the field of expanding renewable energy sources, energy efficiency, etc. In the National Priorities, which provide the vision of Azerbaijan until 2030, sustainable development and environmental protection are defined as one of the main goals. This document contains specific environmental goals, such as accelerating our country's transition to a green economy, efficient management of natural resources, reducing carbon emissions, adapting to climate change and increasing energy efficiency" M. Babayev noted (Bayramova, 2024).

It should be noted that EU4Environment helps Azerbaijan develop green investment strategies, prepare final versions of the Law "On Strategic Environmental Assessment (SEA)" and the Law "On Environmental Impact Assessment (EIA)". EU4Environment (EU4Environment, 2025) also promotes regulatory reform, supports compliance, enhances policy dialogues on green finance and investment, supports public environmental expenditure management, assesses and strengthens administrative capacity, and develops green growth indicators (GGIs).

United Nations to ensure sustainable development, efficient use of resources, as well as equitable distribution, and play a key role in economic development for each country. As a result of cooperation since 1992, several projects have been implemented to increase social welfare and minimize environmental problems.

On March 1, 2021, an agreement covering the years 2021-2025 was signed between the UN Country Group and the Republic of Azerbaijan. The main priorities of the documentary (United Nations, 2021): (1) Development of institutions in the provision of social services. (2) Formation of a society with a gender structure. (3) Protect the environment by protecting against climate change. (4) Ensuring sustainable inclusive growth. The fifth business framework plays a key and stimulating role in achieving sustainable development.

The Government of the Republic of Azerbaijan and the World Bank Group signed an Agreement on Cooperation on November 2021. The main purpose of the agreement was to establish and operate an office of the World Bank in Azerbaijan. This cooperation will play an important role in ensuring socio-economic development and achieving the goals of green and sustainable development. It should be noted that the World Bank has financed more than 50 projects in Azerbaijan to improve the social situation of the population, create new jobs, develop the business environment, increase the competitiveness of agricultural products, develop human capital, and improve the social situation of IDPs. $4.4 billion has been allocated for sustainable development (World Bank Group, 2021).

On February 16, 2022, the European Union and the World Bank signed an agreement for Azerbaijan Rapid Technical Assistance Facility. This agreement Support the development of institutions Improving economic development and market relations Protecting the environment, ensuring energy efficiency allowing for mobility and people-to-people contacts. The main goal of the project is to support the measures taken under the 2030 socio-economic development strategy of Azerbaijan and to provide analytical analysis and advice. €5.25 million has been allocated for the project. Cooperation with the World Bank plays an important role for the Republic of Azerbaijan in developing a green economy, accelerating socio-economic development, ensuring sustainable development, and preventing environmental problems.

Turkey

In 2012, Türkiye tried to maintain its economic balance in an environment of uncertainty stemming from the ongoing recession in the European economies and the political and economic problems prevalent in its neighboring countries. In 2012, the recovery in the global economy could not reach a sufficient level, and basic macroeconomic and financial problems continued.

Turkey, which has an important place in the global economy, is suitable with regards to sectoral diversity, wide production opportunities, modern logistics infrastructure, strategic placement, and qualified workforce, and constitutes a center of attraction in terms of foreign direct investments. Generally, foreign direct investments consist of direct capital investments that cover long-term decisions and long-term portfolio investments. Mainly in recent years, the country's power to attract investment has increased even more in the uncertainties and transformation process of the world economy (Gasimli, 2023, pp. 314–320).

With the elimination of borders with globalizing trade, developing countries are trying to attract foreign capital to their countries due to the lack of domestic savings. Foreign direct capital of Turkey does not only contribute to the capital insufficiency of countries, but it also contributes to the country's economy by providing know-how, technology transfer, and employment directly. Foreign direct investments in Turkey between 2011-2021 have been evaluated. Turkey continues to be an investment attraction center with its widespread R&D centers, intense state incentives in this area, production of innovative products, and strong technological infrastructure. FDI continues to increase the land sea and air transportation to Europe, Asia, and Middle East, constituting a logistic base.

To prevent the negative effects of the COVID-19 epidemic in 2020, the Ministry of Treasury and Finance made some arrangements with the Economy Stability Shield Package announced. Within the scope of the package, sectoral reductions were made in tax rates, the implementation of the accommodation tax was postponed, the existence of force majeure was accepted for taxpayers operating in sectors that were severely affected by the epidemic, and the submission and payment periods of concise, VAT and social security declarations were extended, and all income taxpayers were included in the scope of force majeure, credit conditions were loosened. The scope of the package has been expanded with new measures taken in line with emerging needs (Gasimli, 2023, pp. 222, 235). Within the scope of the Medium-Term Program (2021-2023), it is foreseen that in 2021, in proportion to the success achieved in the fight against the epidemic, the budget revenue collection will increase and a partial tightening will be made by making savings in the areas determined by the efficient use of resources. Furthermore, income -and expenditure-oriented policies were implemented throughout the year, taking into account inflation and demand conditions.

In 2021, within the scope of combating the economic and social effects of the epidemic, there was an increase in expenditures due to the measures implemented to support the real sector and households. However, a strong recovery was observed in income collection as a result of the widespread use of vaccination and the gradual relaxation of the measures taken against the pandemic. In 2021, revenues exceeded expectations, and expenditures were in line with the targets (Gasimli, 2023, p. 234). In June 2022, the International Labor Organization reported that Türkiye could increase its GDP by $8 billion and create more than 300,000 new jobs by 2030 through investments in renewable energy (TRT Global, 2022). In 2022, the EBRD allocated €500 million to Turkey to develop the green economy. The Industrial Development Bank of Turkey (Türkiye Sınai Kalkınma Bankası) was the first bank to benefit from the GEFF programme, with €53.5 million (Kaya, 2022; Yilmaz et al., 2025).

On 28 May 2025, the 4th Poland-Turkey Economic Forum was held in Istanbul, focusing on the theme "Green Technologies and Energy Transformation." Key areas of cooperation included energy, renewable energy sources, chemical industry, contracting services, automotive industry and auto components, medical tourism, agriculture, animal husbandry, infrastructure, ecology, waste management, and logistics. Turkey and Poland are strengthening their collaboration in green energy through joint initiatives aimed at creating sustainable energy systems and combating climate change (Yilmaz et al., 2025). Turkey is set to become the world's 10th largest country in terms of renewable energy capacity, driven primarily by wind and solar power plants. Renewable energy capacity in Turkey is expected to grow by 64% between 2022 and 2027, reaching 90 gigawatts, making it the fourth-largest renewable energy market in Europe and the tenth-largest globally (TRT Global, 2022).

Kazakhstan

The source of long-term economic growth to effectively implement, among other things, the state's social obligations to provide jobs and encourage private businesses in the small and medium-sized enterprise category are large enterprises and national mega-projects. Thus, during the period of independence, according to public information from regional executive authorities, more than 130 major projects worth 4,425.95 billion tenge have been implemented in Kazakhstan in various sectors of the economy.

Some of them are:

– Construction of a copper ore mining and smelting facility in the East Region of Kazakhstan, commissioned in 2017.

– Modernization and reconstruction of the Shymkent oil refinery, with a capacity of 6 million tons of products per year.

– Construction of a mining and processing complex in the Pavlodar Region, with a capacity of 100,000 tons of concentrate per year, started in 2015.

– Gas-processing Plant-2 in the Aktobe Region, launched in three stages (2008, 2015, 2018), with a capacity of over 500,000 tons of gas, 4 million tons of marketable gas, and 3 million tons of marketable oil per year.

– Opening of a tourist and hotel complex in Aktau, Mangystau Region.

– Launch of a wind power plant in the Akmola Region, built according to green standards, with a capacity of 100 MW.

– A hydrocarbon stabilization and purification unit in the West Kazakhstan Region, with a capacity of 2.57 million cubic meters per year, commissioned in 2011.

– Construction of a cement plant in the Almaty Region, completed in 2020.

– Launch of a mining and processing complex and the Koktaszhal deposit in the Karaganda Region, with a capacity of 3 million tons of ore per year.

– Construction of an international airport in the Turkestan Region.

– Opening of a large-panel reinforced concrete factory in Astana in 2016, with a capacity of 134,000 cubic meters per year.

– Construction and commissioning of a cement plant in the Kyzylorda and Zhambyl Regions, with a capacity of 2 million tons of cement per year.

– A small-section rolling mill in Kostanay, with a capacity of 450,000 tons per year.

– An automotive plant in Almaty, launched in two phases, with a capacity of 45,000 units per year as part of an industrial zone.

– Launch of flour and pasta production in the North Kazakhstan Region, in 1998.

Within the framework of Kazakhstan-Türkiye cooperation 61 projects amounting to 2 billion tenge have been implemented, most of them in Almaty city and Almaty region-21 projects, in Shymkent city and Turkestan region-12 projects and in Astana city-7 projects. For example, *Swissgrow Tarim Gida Ambalaj* – organic mineral fertilizer production; *LC Waikiki* – opening and operating of shop chains; *Anadolu Endustri Holding* – soft drink production; *Nobel Pharmaceuticals* – pharmaceuticals production; *Royal Hijyen ve Saglik Urunleri* – nappy production; *YDA* – airport construction and operation; *Aselsan Elektronic* – electronic and electro-optical devices production; and others.

In 2020, taking into account the new reality both in the world and at home, Kazakhstan has formed a “new agenda” of economic development of Kazakhstan until 2025 (actively reforming approaches in the state sectoral policy). For example, in the sphere of agriculture 7 large ecosystems with a focus on the food industry, as well as the development of the fishing industry are to be formed. This year, 51 agro-industrial projects (production and processing of meat, cereals, milk and others) worth 48.7 billion tenge have been launched, creating more than 0.9 thousand new jobs. Sixty agricultural cooperatives have been established, including 55 cooperatives for the production and processing of livestock products. In industry and infrastructure, more than 1,000 projects are expected to be launched, creating more than 5,000 new jobs. (Gasimli, 2023)

As a result of legislative reforms, Kazakhstan was able to significantly accelerate the development of renewable energy, making RES an important component of its energy balance and sustainable development strategy. Today, there is a stable growth in the share of electricity produced by RES. Excluding large hydroelectric power plants, the share of renewable energy sources in the total volume of electricity production in 2023 was 5.82%, with the volume of energy generated to 6.6 billion kWh. It should be noted that since 2014, the installed capacity of renewable energy sources has increased more than 16 times - from 178 MW to 2868 MW by the end of 2023.

According to the results of the first half of 2024, 148 renewable energy stations with a total installed capacity of 2903.7 MW are already successfully operating in Kazakhstan. These stations include 59 wind power plants (WPP), 46 solar power plants (SPP), 40 hydroelectric power plants (HPP) and 3 bioelectric power plants (BioPP). Together, they account for 6.47% of the country’s total electricity production, making a significant contribution to Kazakhstan’s energy balance and confirming the country’s commitment to developing sustainable and environmentally friendly energy sources. According to the Concept for the Transition to a Green Economy, the task is to reduce the energy intensity of the country's GDP by 25% by 2025 and by 50% by 2050 (from the 2008 level). It should be noted that the 2025 indicator was achieved ahead of schedule: in 2021, a reduction in the energy intensity of GDP by 38.5% from the 2008 level was achieved.

Industry. The goal is to reduce energy intensity by 10% by 2029. This involves the introduction of energy-efficient technologies and the modernization of production processes in large industrial enterprises.

Energy. In this sector, it is planned to reduce energy intensity by 5% by 2029. This is planned to be achieved by optimizing energy infrastructure, improving production technologies and energy distribution.

Transport. The concept also covers measures to reduce energy intensity in the transport sector, which includes a transition to more environmentally friendly and energy-efficient modes of transport (PAGE, 2020). The lack of sustainable finance is one of the biggest obstacles to greening the economy. The average annual gap in long-term green finance is estimated at $2.3 billion, with the EBRD, the European Investment Bank (EIB) and the European Union (EU) providing the bulk of green finance (PAGE, 2020; KazISS, 2024).

Uzbekistan

Investment cooperation between Uzbekistan and the countries of the Turkic World is developing dynamically. Major projects are being implemented within the framework of cooperation in this area. The analysis of investments by industry showed that the largest share (65%) is invested in the manufacturing industry. A high share of investments was in agriculture (13% of the total investment). Investments in housing and communal services and nutrition accounted for 9.3%, construction 6.5%, public administration, wholesale and retail trade 1.5% and 1.3%, respectively. Turkish entrepreneurs have invested in water supply, sewerage and waste collection as well as in healthcare. 50 projects worth $594.55 million have already been implemented, 39 projects worth $985.88 million are under implementation, 21 projects worth $758.4 million are still scheduled to be completed (Gasimli, 2023, p. 308).

As of the beginning of 2022, five major energy projects with a total capacity of 1.4 thousand megawatts have been implemented jointly with Turkish companies over the past year. The second combined-cycle unit of the Navoi thermal power plant with the participation of the Turkish company Calik Enerji has been put into operation. In March 2022, a 240-megawatt thermal power plant was launched in the Qibray district of Tashkent region and the construction of a thermal power plant in the Khavast district of the Sirdaryo region has started.

At the same time, over the past five years, after Uzbekistan began large-scale reforms in all spheres of life, regional cooperation and interaction between the countries of the region in various areas, including in the water and energy sector, has significantly expanded. There is also an expansion of cooperation in the energy sector with Kazakh stan and Turkmenistan. Together with Tajikistan, Uzbekistan plans to build 2 hydroelectric power plants with a capacity of 320 megawatts on the Zarafshan River and expressed its readiness to participate in the construction projects of the Kambar–Ata (Kyrgyzstan) and Rogun (Tajikistan) hydroelectric power plants.

An important step in developing common approaches of the countries of the region to the rational and efficient use of resources can be the adoption of the regional program “Green Agenda”, which will lay the foundation for sustainable “green” development of the entire region (Gasimli, 2023, pp. 308–309). Uzbekistan creates Engineering and Technology Centers based on existing specialized organizations of the OTS countries. Their activities will be aimed at the formation of value chains and the development of joint projects based on the principles of competitiveness.

Turkey takes active part in improving of digitalization processes in various fields and the creation of a permanent platform for experts and IT specialists to exchange experience and transfer innovations to create “smart” cities. Turkey modernized the energy sector of Uzbekistan. This project will provide an additional 71 billion kWh of electricity. Twelve billion cubic meters of natural gas per year will be saved. It is important to cooperate in environmental issues and environmental protection, first at all, to improve the situation around the Aral Sea. Joint efforts are required in the transition to a new, innovative and technological model of development, including the introduction of “green”, environmentally friendly, energy-saving and safe technologies, the implementation of initiatives to mitigate the consequences of environmental crises and environmental protection for sustainable development. Initiatives are aimed at forming a permanent Platform of experts and IT specialists as well as an environmental protection structure of the Turkic States with headquarters in the Aral Sea region, the region most affected by the environmental disaster. “Development Strategy of the New Uzbekistan for 2022-2026” has got a separate goal: “Raising to a high level of close cooperation in the field of security, trade and economic, water, energy, transport and cultural and humanitarian spheres in Central Asia.”

Uzbekistan has successfully addressed several green economy challenges through the following measures:

– to expand mutually beneficial cooperation in the energy sector, with particular attention to the introduction of “green” energy and energy-efficient technologies;

– to hold regular meetings of agriculture ministers of the countries in the region and to develop a regional food security monitoring system;

– to develop a regional program, *Green Agenda for Central Asia*, which would contribute to the adaptation of the countries in the region to climate change, as well as to the wider introduction of resource-saving technologies;

– to create a Center for Research on Trade Cooperation of the Turkic States, tasked with developing proposals for eliminating trade barriers, promoting the widespread introduction of e-commerce, and increasing exports and imports;

– to strengthen industrial cooperation and implement major investment projects, including the establishment of an Investment Fund and a Development Bank of the Turkic Council, the creation of Engineering and Technology Centers based on specialized organizations of member states to develop joint projects, and the holding of the *Week of Industry of the Turkic States* in Uzbekistan in 2022;

– to create a permanent platform of experts and IT specialists for the exchange of experience and transfer of innovations for the creation of smart cities, including the organization of an expert conference in 2022;

– to promote the practical implementation of the joint program *One Tour–the Whole Region*, covering the entire spectrum of tourist destinations.

In order to implement the objectives defined in the Development Strategy of the New Uzbekistan for 2022–2026, a series of measures is being undertaken to ensure green and inclusive economic growth, as well as to further expand the use of renewable energy sources and resource-saving technologies across all sectors of the economy. Key legislative and strategic documents have been adopted, including the Laws *On the Use of Renewable Energy Sources* and *On Hydrometeorological Activities*, the Concept of Environmental Protection of the Republic of Uzbekistan until 2030, and the Strategy for the Transition of the Republic of Uzbekistan to a Green Economy for the Period 2019–2030. In 2023–2024, a green energy certificate system was introduced to control the quality of products and processes produced using environmentally friendly technologies and renewable energy sources, among other initiatives. By 2030, Uzbekistan aims to reduce greenhouse gas emissions by 35% per unit of GDP.

Kyrgyzstan

The state policy framework of the republic contributes to the development of a green economy and stimulates the private sector in transitioning to green business principles. The state policy agenda envisages the following measures (Gasimli, 2023):

– involvement of mass media, especially state and public outlets, to raise awareness among businesses and the population, and to promote the green agenda aimed at fostering environmental responsibility and transforming the culture of thinking;

– organization of awareness-raising activities for the private sector on the introduction of green practices through specialized regional training structures;

– revision of outdated state standards, construction codes, and regulations inherited from the Soviet period, which currently hinder the application of green economy principles, particularly regarding energy efficiency and conservation in the construction sector;

– promotion of green fiscal measures in the new edition of the Tax Code of the Kyrgyz Republic, along with the development of mechanisms for their implementation through private sector participation;

– ensuring the sustainability and continuity of state policy promoting green economy principles, with particular emphasis on the energy and agriculture sectors;

– advancement of data-driven measures for green economy development;

– promotion of potential green initiatives to support sustainable business within the Eurasian Economic Union (EAEU);

– intensification of efforts to attract sustainable financing in the Kyrgyz Republic, including the establishment of a green financial corporation;

– development of a green taxonomy to facilitate the inflow of green investment into the Kyrgyz Republic;

– consolidation of efforts and increased private sector participation in developing climate adaptation measures and fostering a sustainable business environment;

– creation of financial instruments and engagement of the financial sector in implementing the climate and green economy agenda.

At the UN Conference on Sustainable Development "RIO+20" in 2012, Kyrgyzstan expressed its commitment to sustainable development through the promotion of "green economy" priorities. Currently, the Kyrgyz Republic is pursuing an active policy aimed at forming and strengthening its economic potential in accordance with the main strategic guidelines and objectives set out in the National Sustainable Development Strategy. The strategic sectors of the economy in the Kyrgyz Republic include agriculture, manufacturing and processing industry, energy, mining, transport, construction, and tourism. In the industrial sector, there is a need to increase the potential of manufacturing enterprises by reducing energy costs, creating mechanisms to stimulate the introduction of resource-saving and low-waste technologies, ensuring the rational use of local labor resources, and minimizing environmental impacts. The presence of its own mineral resource base is a great advantage for the Kyrgyz Republic, and its development can significantly increase the country's GDP and tax revenues to the state budget. Particular attention should be paid to toxic waste storage facilities that remain in the country after the closure of mining enterprises and require significant financial investments to maintain them in proper condition and eliminate negative impacts. The priority areas of this sector are the modernization of management (administration) of the mining industry, harmonization and increased efficiency of the legal regulation system, improvement of the system of access to subsoil use rights and subsoil use administration, improvement of the taxation system, reduction of environmental impacts, mitigation of potential conflicts (relations with the local population), training of professional personnel, and support and stimulation of small mining businesses. In the field of tourism, the current tasks remain the creation of conditions for the formation of sustainable and competitive tourism products and services while preserving cultural and historical sites and ensuring minimal negative environmental impact, as well as increasing the effectiveness of state regulation of tourism industry development.

At the national level, it is recommended to take measures to increase the human and institutional capacity of all key stakeholders to develop a green economy in the country and to integrate the principles of a green economy into education, fiscal policy, tariffs, public procurement, and subsidies (PAGE, 2017). It is also necessary to provide support to the Government in conducting economic valuation of natural capital and ecosystems, as well as in building an effective monitoring system in accordance with international and national development strategies.

Conclusions

The essence of applying the principles of a green economy lies not in whether economic growth or competitiveness increases or decreases. The green economy promotes not only economic growth but also genuine development, taking into account the conservation of the planet's resources for future generations. The GDP indicator alone does not reflect the true nature of public welfare. Until now, economic growth has largely relied on borrowing from future generations — achieved at the expense of natural resources and environmental degradation. Such practices effectively make future generations poorer, even though this is not captured by GDP. In this context, the green economy should advance the following key components:

– The essence of the green economy lies in improving human well-being, promoting social equity, and reducing environmental risks under conditions of uncertainty. Therefore, innovative and inclusive growth, along with the adoption of "green" GDP, are of key importance.

– A balanced integration of ecological considerations with economic growth and national development contributes to reducing environmental problems, enhancing sustainability, increasing resource-use efficiency, and reinforcing the overall importance of the green economy.

– The green economy fosters higher efficiency and effectiveness, improved governance, better coordination among stakeholders, and ultimately greater public well-being.

– The growing influence of the green economy drives structural transformations across all sectors of the national economy.

– The Green GDP Index reflects economic growth while accounting for environmental pressures and resource depletion.

– The green economy is not limited to the use of renewable energy sources. It is a broader conceptual framework aimed at establishing and implementing new production and consumption models that differ fundamentally from traditional ones, ensuring not only profit generation but also the fulfilment of societal needs.

– The assessment of the environmental component within the Green GDP Index relies on economic indicators, thereby simplifying and streamlining the conceptual framework.

– Enhancing efficiency and governance effectiveness will create the foundation for inclusive growth and development — providing equitable socio-economic opportunities for all members of society and enabling the realization of their creative potential. Such growth and development will also support structural adjustments in the economy in line with global trends.

To solve existing structural problems, a systematic approach is essential because it affects modernization, efficiency, and diversification and thus increases national competitiveness and sustainability. For this purpose, the following methodological toolkit is advisable: divergence (a structured study of the current situation); convergence (an assessment that identifies commonalities and consolidates findings); and transformation (an analysis of the problem structure with the aim of identifying independent components that should be modified in response to changes in the external environment). A systemic approach therefore entails not only identifying existing shortcomings but also defining them precisely, detecting previously unrecognized system elements, and determining a sequenced program of changes designed to achieve qualitative improvements in development.

Technological innovation, and the manner of its deployment, is critical for enabling industry to generate new commercial value while also delivering benefits to people and the environment. Green employment is a specific dimension of green economic development that integrates economic and environmental objectives. In recent years manufacturing firms have advanced their efforts toward sustainable manufacturing, shifting from narrow pollution-prevention measures to integrated approaches that incorporate product lifecycle perspectives and wider socio-environmental implications. Eco-innovation supports this evolution by combining technological and non-technological advances that can produce substantial environmental benefits.

Financial and institutional mechanisms are most often used to achieve sustainable development goals. The implementation of green projects typically foresees state support from the budget or financing from development institutions; however, a persistent problem is the lack of guaranteed payment streams from budgetary organizations or local authorities. In international practice, that problem is addressed by establishing specialized green funds or dedicated legal entities with the prospect of subsequent capitalization. Primary financing sources for such vehicles may include budgetary resources (direct and indirect state and utility investments), credit instruments of international organizations (e.g., technical assistance), and carbon taxation. Empirical experience shows wide variation in financing structures: international development institutions have provided between 20% and 80% of initial capital for national green banks/funds (for example, Kazakhstan and Kyrgyzstan, respectively); central governments' shares have ranged from about 10% to 80% (for example, Uganda and Zambia); and private capital participation typically ranges from 10% to 30% (for example, Kenya, Kyrgyzstan, Mongolia). In addition, private philanthropic and quasi-public instruments that supply grant-based capital (for example, crowdfunding or voluntary contributions) can also be mobilized.

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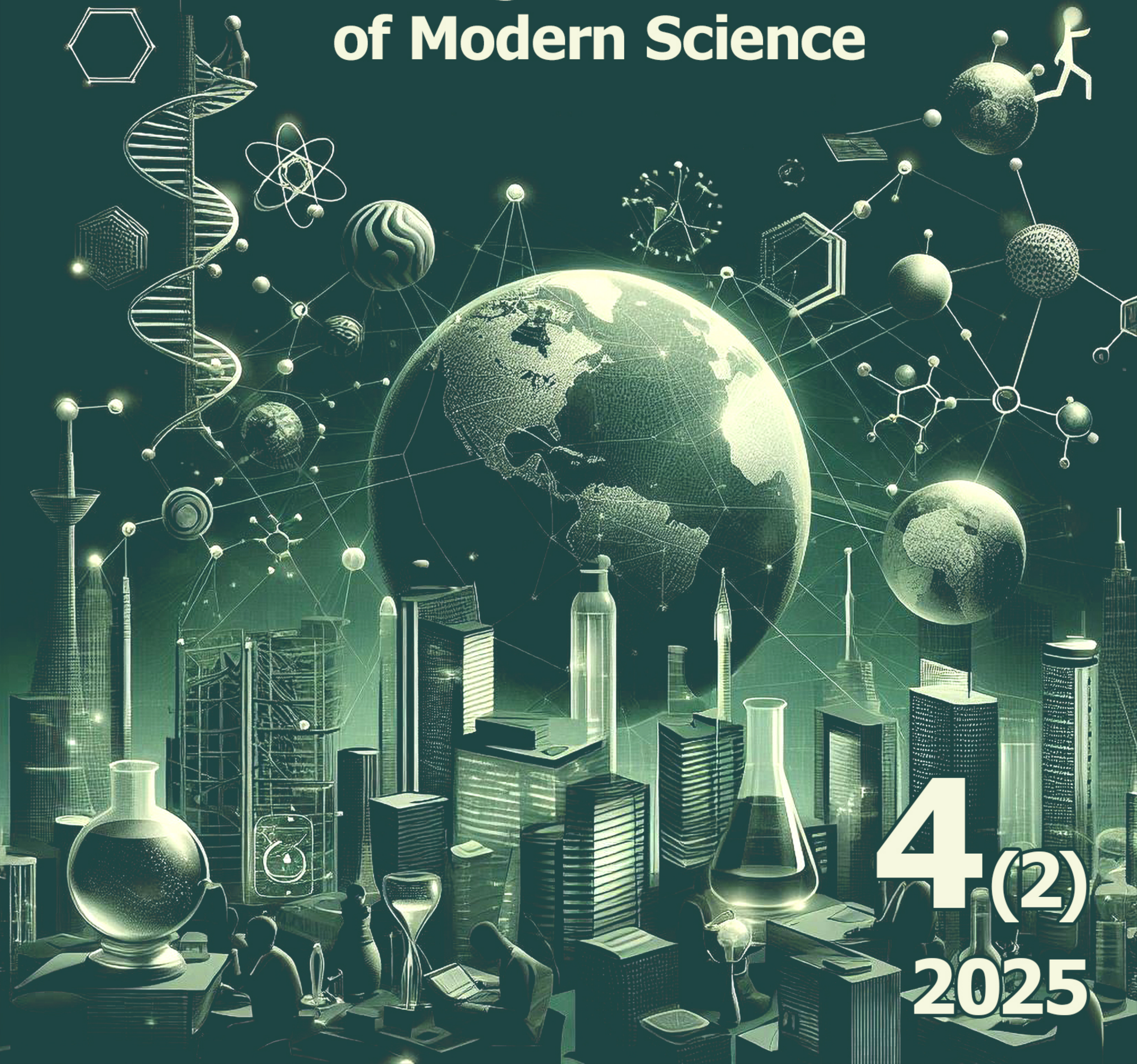

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