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HUMAN CAPITAL MANAGEMENT, PROFESSIONAL EDUCATION AND FINANCIAL SUPPORT FOR SUSTAINABLE DEVELOPMENT OF AGRITOURISM

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ABSTRACT

The article is devoted to the development and practical testing of the author's adaptive multi-level synergistic model for assessing the sustainable development of agrarian tourism enterprises, which integrates human capital management, professional education, and financial support into a single system of support for management decisions. The relevance of the study is due to the need to form new methodological approaches to the comprehensive assessment of the sustainable development of agrarian tourism enterprises in the context of digital transformation, increased competition, instability of the economic environment, and the growth of the role of human capital as a strategic factor of competitiveness. The methodological basis of the study is the author's AMSAM model, which combines adaptive nonlinear transformation of indicators, parametric Tsallis entropy for determining the information significance of criteria, the method of hierarchy analysis, a logistic mechanism for integrating statistical and expert weighting coefficients, regularized Mahalanobis distance for taking into account the correlation structure of data, and synergistic aggregation of integral estimates. Practical testing of the model was carried out on a sample of Ukrainian agrarian tourism enterprises using open information and expert assessment of indicators not presented in financial statements. Scientific support for expert assessment and verification of the consistency of weighting coefficients was provided with the participation of specialists from the Oleksandr Dovzhenko Hlukhiv National Pedagogical University (Ukraine) and the International Academy of Applied Sciences in Lomza (Poland). The results of the study confirmed the high discriminatory ability of the proposed model and its ability to comprehensively assess the level of sustainable development of enterprises. The proposed methodological approach is universal in nature and can be adapted for assessing enterprises in other sectors of the economy, whose activities are based on the effective use of human capital, knowledge, and financial resources.

Keywords: sustainable development, agrarian tourism, agrarian tourism enterprises, human capital management, vocational education, financial support

JEL Classification: J24, M12, Q01, Q13, Z32

INTRODUCTION

Sustainable development of agritourism is becoming increasingly important as one of the key areas of diversification of the rural economy, ensuring employment of the population and increasing the competitiveness of territorial communities. The combination of tourism activities with agricultural production creates the prerequisites for the formation of new sources of income, preservation of cultural heritage, development of local entrepreneurship and activation of innovative processes in rural areas. At the same time, the modern development of agritourism enterprises takes place in conditions of high variability of the external environment, characterized by the transformation of consumer demand, digitalization of business processes, shortage of qualified personnel, increasing financial risks, climate challenges and the need to integrate the principles of sustainable development into the enterprise management system. Under such conditions, financial results can no longer be considered as the only criterion for the effec-

tiveness of the functioning of agritourism entities. The quality of human capital management, the level of professional education of personnel, the ability of the enterprise to accumulate knowledge, adapt to changes, introduce innovations, and ensure the effective use of financial resources are of decisive importance. It is the interaction of these components that forms the long-term sustainability of the enterprise and determines its potential for ensuring economic, social, and environmental performance.

In modern scientific literature, a significant number of models for the integrated assessment of enterprise development have been proposed, among which the most widespread are the method of hierarchy analysis, the entropy approach, TOPSIS, VIKOR, COPRAS, WASPAS, EDAS and other methods of multi-criteria decision-making. Their application has made it possible to significantly increase the objectivity of the assessment of complex economic systems and form new approaches to ranking alternatives. However, most existing models are based on linear normalization of indicators, the use of fixed weight coefficients, and the assumption of independence of assessment criteria.

At the same time, the functioning of agrarian tourism enterprises is characterized by a high level of interdependence between individual components of development. In particular, increasing financial security does not guarantee improved performance without the appropriate development of human capital, while investments in vocational education do not provide the necessary economic effect in the absence of financial resources for the implementation of the acquired competencies. Thus, a synergistic interaction arises between human capital, professional education, and financial support, which is practically not taken into account by existing models of integrated assessment.

The issue of adaptive formation of weight coefficients also remains insufficiently studied. In most models, the ratio between expert assessments and statistical information is determined by pre-established coefficients, which do not take into account the heterogeneity of the information base, the level of variability of indicators, and the quality of the initial data. As a result, the final assessment results may significantly depend on the subjective choice of the researcher, and not on the real characteristics of the enterprises under study.

The above methodological limitations necessitate the development of a new model of comprehensive assessment, which would combine adaptive transformation of indicators, modern entropic approaches to determining the information significance of criteria, expert structuring of priorities, taking into account correlation relationships between indicators and assessing the synergistic interaction of key components of sustainable development.

In this regard, the study proposes the author's Adaptive Multi-layer Synergistic Assessment Model (AMSAM) - an adaptive multi-level synergistic assessment model based on nonlinear transformation of indicators according to their target intervals, the use of Tsallis entropy to determine the information weight of criteria, the dynamic combination of expert and statistical weights, the application of regularized Mahalanobis distance, and the calculation of the integral synergistic index of sustainable development of agrotourism enterprises.

LITERATURE REVIEW

Analysis of scientific sources shows that the sustainable development of agritourism enterprises is interdisciplinary in nature and requires careful consideration of human capital, professional education, financial support, innovative management, digitalization, environmental responsibility, and risks.

The first group consists of studies devoted directly to the development of agritourism and rural tourism. Park et al. (2014) identified management competencies, strategic planning, and customer orientation as key factors for the success of farm tourism. Sgroi et al. (2018) substantiated the role of state financial support in shaping the competitive advantages of agritourism enterprises, and Ingrassia et al. (2023) linked their sustainable development with the principles of the circular economy and responsible behavior of farmers and tourists. Liu et al. (2023) confirmed the positive impact of integrating agriculture and tourism on the green development of territories. The importance of state support for small and medium-sized agritourism businesses was revealed by Sangnak (2025), while Siregar et al. (2024) focused on the entrepreneurial competencies of rural youth. Global trends, limitations, and prospects for agritourism research were systematized by Yasin and Bacsi (2025).

The second group is formed by works on human capital management and professional education. Bindawas (2025) and Ernawati et al. (2022) prove that the quality of tourism services and the implementation of sustainable practices directly depend on professional skills, continuous learning, and environmental competencies of personnel. The socio-psychological content of professional activity, communicative abilities, and responsibility of specialists were revealed by Bosniuk et al. (2021). Plakhonik et al. (2024) investigated the organizational and motivational principles of effective management of the educational environment, and Voznyuk et al. (2022) substantiated the use of a synergistic approach and self-managed

teams in the educational sector. The problems of a responsible and inclusive tourism labor market in the context of the Sustainable Development Goals were considered by Vazquez-Garcia et al. (2026).

The third group of sources covers financial, innovative, and institutional support for enterprise development. Bilan et al. (2017) emphasized the need to take into account the social component in resource management. Bondarchuk et al. (2023) investigated the innovative design of financial and management accounting in the context of migration, information, and security risks. The combination of financial, marketing, and environmental mechanisms of agribusiness management was substantiated by Tereshchenko et al. (2023). Prokopenko et al. (2021) revealed the role of clustering, state regulation, marketing, and the labor market in the development of the service sector. Institutional and external financial risks of innovative development management were analyzed by Zhyvko et al. (2024).

The fourth group includes studies of digitalization and information and analytical support of management decisions. Chernyavska et al. (2023) showed the possibilities of using artificial intelligence to attract financing and process management information. Mykhalchenkova et al. (2024) identified information hubs as important tools for disseminating innovations and supporting business dynamics. Naumenko et al. (2024) substantiated the use of adaptive modeling and data analysis technologies in crisis management of enterprises, which is important for the seasonal and risky environment of agrarian tourism.

A separate group is formed by works that have methodological significance for assessing human capital, professional risks, and management efficiency. Gažarová et al. (2025) demonstrated the possibilities of using weight-adjusted integral indices for a comprehensive assessment of interrelated indicators. Sharlovych et al. (2025a) investigated the relationship between occupational risks and the quality of life of employees, which is important for assessing personnel stability and working conditions. Sharlovych et al. (2025b) substantiated the management of organizations based on a systematic assessment of performance.

Thus, the studies considered form an appropriate theoretical basis for the analysis of agrarian tourism, human capital, professional education, financing, digitalization, and risks. At the same time, the scientific literature does not sufficiently present comprehensive models that simultaneously take into account the nonlinearity of indicators, statistical and expert weights, correlations, risks, and synergistic interaction of personnel, educational and financial components. This necessitates the development of an adaptive multi-level synergistic model AMSAM for assessing the sustainable development of agrarian tourism enterprises.

AIMS AND OBJECTIVES

The purpose of the article is to develop and practically test the author's adaptive multi-level synergistic model AMSAM for a comprehensive assessment of the sustainable development of agrarian tourism enterprises based on integrated consideration of human capital management, professional education, financial support, and their synergistic interaction.

To achieve the goal, the following research tasks were defined:

1. To generalize scientific approaches to assessing the sustainable development of agrarian tourism enterprises.
2. To develop the author's adaptive multi-level synergistic model AMSAM.
3. To form a system of indicators of human capital management, professional education, and financial support.
4. To carry out practical testing of the model on a sample of agrarian tourism enterprises and assess the level of their sustainable development.
5. To substantiate the possibilities of practical use of the model to support management decisions.

METHODS

Comprehensive assessment of sustainable development of agritourism enterprises requires the use of a methodological approach that ensures simultaneous consideration of economic, social, personnel, and educational factors, as well as their interrelationships. Unlike traditional models of integrated assessment, the proposed methodology is based on the assumption that the efficiency of the enterprise's functioning is formed not by separate groups of indicators, but as a result of their synergistic interaction. The methodological basis of the study is the author's Adaptive Multi-layer Synergistic Assessment Model (AMSAM) – an adaptive multi-level synergistic assessment model designed to determine the integrated level

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of sustainable development of agritourism enterprises through a comprehensive analysis of human capital management, professional education and financial support, taking into account operational risks.

The AMSAM concept is based on several fundamental principles.

First, none of the indicators is considered to be absolutely stimulating or absolutely discouraging. For each criterion, an economically feasible target interval is determined, within which the most effective state of the enterprise is characterized. Accordingly, it is not the direction of change of the indicator that is assessed, but the degree of its compliance with the optimal area.

Secondly, the importance of individual criteria is not a constant value. It is formed by combining statistical information about the variability of indicators and expert assessment of their strategic importance. In this case, the ratio between the objective and expert components automatically changes depending on the structure of the input data.

Thirdly, the model takes into account the interdependence of indicators. Unlike most existing multi-criteria evaluation methods, in which all criteria are considered independent, AMSAM uses a covariance data structure, which allows you to avoid duplication of information and more objectively determine the distance of the enterprise to the reference state.

Fourthly, the integral indicator is formed not by simply adding individual indicators, but by assessing the synergistic interaction between the development of human capital, professional education, and financial support. This approach allows us to take into account that a high value of one component cannot fully compensate for the low level of development of another. To test the proposed model, a sample of seven agrarian tourism enterprises was used, which differ in the scale of activity, financial results, human resources potential, and level of development of tourism infrastructure. This approach provides an opportunity to assess the universality of the model and verify its ability to correctly differentiate enterprises by the level of sustainable development. The information base of the study was formed by combining open financial information of enterprises, data from official websites, statistical materials, as well as expert assessment of indicators that are not reflected in financial reporting. The latter include the level of digital competencies of personnel, the effectiveness of professional training, the degree of cooperation with educational institutions, the quality of knowledge management, and certain characteristics of the risk environment.

To ensure the comprehensiveness of the assessment, all indicators were combined into three functional blocks that correspond to the concept of sustainable development of agrarian tourism enterprises.

The first block characterizes human capital management and reflects the personnel potential of the enterprise, the professional structure of personnel, labor productivity, personnel stability, and the level of digital competencies.

The second block describes the system of vocational education, covering the intensity of employee training, the volume of investments in the development of competencies, cooperation with educational institutions, the practical use of acquired knowledge, and the effectiveness of advanced training programs.

The third block reflects the financial support of sustainable development and includes indicators of profitability, liquidity, financial autonomy, investment activity, and financing of human capital development. An integral risk indicator is formed separately, which characterizes the influence of external and internal factors on the stability of the enterprise's functioning. It includes the risks of seasonality, instability of demand, personnel shortage, financial constraints, digital threats, and other factors that may affect the long-term sustainability of agrarian tourism enterprises.

Thus, the proposed methodology combines statistical analysis methods, expert assessments, nonlinear mathematical modeling, and a synergistic approach to assessment, which allows obtaining an integral characteristic of the sustainable development of enterprises and forming a scientifically sound basis for making management decisions.

A. Nonlinear adaptive transformation of indicators

The first stage of implementing the author's AMSAM model is to reduce heterogeneous indicators to a single dimensionless scale. Unlike most existing multi-criteria evaluation methods, the proposed approach is not based on the traditional division of indicators into stimulants and de-stimulators. Such a division significantly simplifies the economic nature of the studied processes, since it assumes a monotonic effect of each indicator on the integral result. However, in the conditions of operation of agrarian tourism enterprises, a significant part of the characteristics has a nonlinear dependence on the level of sustainable development. In particular, an excessive increase in the share of loan capital, expenses for professional training, or the number of administrative personnel does not always contribute to increasing the efficiency of activities. Similarly, an insufficient level of financing of human capital, low intensity of personnel training, or a deficit of investments negatively affect the development of the enterprise. Thus, for most economic indicators there is a certain area of optimal

values, deviation from which in any direction reduces the overall efficiency of operation. In order to eliminate this shortcoming, an adaptive competitiveness index (ACI) was proposed, which assesses not the absolute level of the indicator, but the degree of its approximation to the economically justified target value.

For the i-th enterprise and the j-th indicator, the ACI coefficient is determined by the formula:

$$ACIij = exp - \frac{xij - xj^*}{\sigma j}^2,$$

where: $ACIij$ *– adaptive compliance coefficient;* xij *– actual value of the jth indicator for the ith enterprise;* xj^* *– target (reference) value of the indicator;* σj *– permissible deviation of the indicator from its optimal level.*

The proposed function has a number of fundamental advantages compared to traditional normalization methods.

First, the maximum value of the coefficient is equal to one only if the actual indicator completely coincides with its target value. This means that the model does not evaluate the maximization or minimization of the indicator, but the achievement of the most effective level of its development.

Secondly, the deviation of the indicator in any direction from the optimal value automatically reduces the value of the coefficient. Thus, the model equally takes into account both insufficient and excessive development of individual characteristics of the enterprise.

Thirdly, the use of the parameter σj\sigma_jσj ensures the adaptability of the model to the features of individual groups of indicators. For criteria with high natural variability, a wider interval of effective values is allowed, while for strategically important indicators the optimum region can be significantly narrowed. As a result of applying the adaptive correspondence coefficient, all indicators acquire values in the range from 0 to 1, which provides the possibility of their further integration regardless of the units of measurement and the scale of the initial data. In addition, such a transformation allows minimizing the influence of extreme observations and ensures the stability of the model to the presence of outliers in the statistical data. The obtained matrix of adaptive coefficients is the initial information base for determining the information significance of the criteria at the next stage of the study using the parametric Tsallis entropy. It is this stage that allows moving from a simple transformation of indicators to an assessment of their real contribution to the formation of the integral index of sustainable development.

B. Determining the informational weight of indicators using Tsallis entropy

After performing the adaptive transformation of indicators, a necessary stage is to determine their informational significance. In traditional entropy models, Shannon entropy is most often used, which characterizes the degree of uncertainty of the statistical distribution. However, the use of this approach assumes the additivity of information and does not sufficiently take into account the nonlinear nature of economic processes inherent in complex socio-economic systems. Agritourism enterprises operate in an environment where the relationships between financial, personnel, and educational indicators are nonlinear in nature. In such conditions, the use of classical entropy can lead to an underestimation of the influence of individual criteria, especially in the presence of high concentration or, conversely, significant heterogeneity of information. In order to eliminate this limitation, the proposed model uses parametric Tsallis entropy, which is a generalization of classical entropy and allows you to adjust the sensitivity of the model to the features of the structure of the source data.

At the first stage, a normalized information distribution is formed for each indicator:

$$pij = \frac{ACIij}{\sum_{i=1}^{m} ACIij},$$

where: pij *– relative information share of the jth indicator for the ith enterprise;* M *– number of enterprises participating in the study.*

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After that, the Tsallis entropy is determined for each criterion:

$$E_j = \frac{1 - \sum_{i=1}^{m} p_{ij}^{q}}{q - 1},$$

where: E_j *– entropy of the jth criterion;* q *– entropy nonlinearity parameter;* $q > 0, q \neq 1$.

The parameter q determines the level of sensitivity of the model to the heterogeneity of the information distribution. For values of q close to unity, the model approaches the classical Shannon entropy. With an increase in the nonlinearity parameter, the sensitivity to indicators with a more pronounced information structure increases, which allows better differentiation of criteria by the level of their contribution to the formation of the integral assessment. The resulting entropy estimates do not characterize the importance of the criteria themselves, but only reflect the level of information ordering of the corresponding indicators. Therefore, at the next stage, the coefficient of information utility is determined:

$$Dj = 1 - \frac{Ej}{\sum_{j=1}^{n} Ej},$$

where: Dj *– informational significance of the jth criterion;* n *– number of model indicators.*

The larger the value of the coefficient Dj, the greater the contribution of the corresponding indicator to explaining the differences between enterprises. At the same time, criteria for which the information is almost the same for all objects of the study receive less weight, since their discriminatory potential is lower. To ensure the possibility of further aggregation, all coefficients of information significance are normalized:

$$w_j^{(E)} = \frac{Dj}{\sum_{j=1}^{n} Dj},$$

where: $w_j^{(E)}$ *– entropy weight of the jth indicator.*

The resulting weight vector reflects the objective statistical importance of each criterion without taking into account expert judgments. Thus, the model automatically enhances the influence of indicators that most differentiate enterprises in terms of the level of sustainable development and reduces the significance of criteria with low information variability. The use of Tsallis entropy has a number of methodological advantages compared to traditional entropy models. First, the nonlinearity parameter allows you to adapt the model to the structure of the input data without changing the overall architecture of the algorithm. Second, the proposed approach provides more stable results in the presence of asymmetric distributions and high concentration of individual indicators. Third, Tsallis entropy better reflects the features of complex socio-economic systems, in which the relationships between the criteria cannot be described exclusively by linear dependencies. At the same time, statistical information does not always reflect the strategic importance of individual indicators for ensuring the sustainable development of agritourism enterprises. That is why, at the next stage of the study, objective entropy weights are integrated with expert assessments obtained by the analytic hierarchy process (AHP) method, which allows forming a balanced system of weighting coefficients that combines the advantages of statistical analysis and professional expert judgment.

C. Formation of an adaptive system of weight coefficients based on expert assessments and logistic combination

Objective weight coefficients obtained using Tsallis entropy characterize the statistical informativeness of indicators, but do not always reflect their strategic importance for ensuring the sustainable development of agrarian tourism enterprises. For example, a separate indicator may demonstrate insignificant statistical variability among the studied enterprises, but at the same time be decisive for the formation of long-term competitive advantages. That is why the use of an exclusively entropic approach does not ensure full consideration of the specifics of management processes. In order to eliminate this drawback, the Analytic Hierarchy Process (AHP) method was applied in the author's AMSAM model, which allows determining the expert significance of each criterion by comparing indicators in pairs. At the first stage, a matrix of pairwise comparisons is formed:

$$A = (aij)_{n \times n},$$

where: aij *– expert assessment of the superiority of the i-th criterion over the j-th;* n *– number of criteria.*

Based on the normalized matrix, expert weight coefficients are determined:

$$w_j^{(A)} = \frac{\sqrt[n]{\prod_{j=1}^{n} aij}}{\sum_{j=1}^{n} \sqrt[n]{\prod_{j=1}^{n} aij}},$$

where: $w_j^{(A)}$ *— expert weight of the jth indicator.*

The obtained weight coefficients reflect the professional vision of experts regarding the strategic importance of individual characteristics of sustainable development of enterprises. At the same time, the analysis of modern methods shows that most researchers combine statistical and expert weights by simply averaging them or using fixed coefficients. Such an approach is not sufficiently justified, since the ratio between objective information and expert estimates should change depending on the structure of the source data. In this regard, the author's mechanism for logistic combination of weights is proposed in the work, which automatically determines the degree of confidence in statistical and expert information. For this purpose, an adaptive coefficient is introduced:

$$\lambda = \frac{1}{1 + exp - k\,V - \bar{V}},$$

where: λ *– adaptive combination coefficient;* V *– average coefficient of variation of the initial indicators;* $\bar{V}$ *– variation threshold value;* k *– sensitivity parameter of the logistic function.*

The economic content of the proposed dependence is that with increasing heterogeneity of statistical data, their information value increases, and therefore the model automatically increases the weight of the entropy component. If the initial indicators are characterized by insignificant variability, expert assessments acquire greater weight, which allows taking into account the strategic features of enterprise development. The final integrated weight coefficients are defined as:

$$Wj = \lambda w_j^{(E)} + (1 - \lambda) w_j^{(A)},$$

where: Wj *– integral weight of the jth indicator;* $w_j^{(E)}$ *– entropy weight;* $w_j^{(A)}$ *– expert weight.* After that, a control normalization of the weight coefficients is performed:

$$\widetilde{Wj} = \frac{Wj}{\sum_{j=1}^{n} Wj},$$

where: $\widetilde{Wj}$ *– final normalized weight of the criterion.*

The proposed approach has several fundamental advantages compared to traditional multi-criteria evaluation methods. First, there is no need to subjectively set the ratio between statistical and expert weights. Second, the model automatically adapts to the characteristics of the sample, providing greater flexibility in evaluation. Third, the logistic function eliminates sharp jumps in weight coefficients, which increases the stability of the integral index to changes in the information structure of the source data. As a result of the third stage, the final vector of weight coefficients is formed, which is used to determine the integral level of sustainable development of agrarian tourism enterprises. Unlike classical multi-criteria analysis models, in which the weights remain constant throughout the study, the proposed system provides their adaptive adjustment depending on the statistical characteristics of the information base, which increases the reliability of the results obtained and expands the possibilities of practical application of the model.

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D. Construction of the integral synergistic index AMSAM

After determining the adaptive weight coefficients, the next stage is the integral assessment of the level of sustainable development of agritourism enterprises. In most existing models of multi-criteria analysis, the assessment is carried out by determining the Euclidean distance between alternatives and a certain reference solution. However, this approach is based on the assumption of statistical independence of criteria, which practically does not correspond to the peculiarities of the functioning of real economic systems. For agritourism enterprises, human capital, professional education, and financial support form a single interconnected system. Changing one indicator inevitably affects other characteristics of the enterprise's development. That is why the use of the Euclidean metric can lead to double consideration of individual factors and distortion of the integral assessment. In order to eliminate this drawback, the proposed model uses the regularized Mahalanobis distance, which takes into account the covariance structure of the initial data and provides a more accurate determination of the proximity of the enterprise to the reference state.

The reference vector is formed as a set of the best values of adaptively transformed indicators:

$$z^* = (z_1^*, z_2^*, \ldots, z_n^*),$$

where: z_j^* *– the optimal value of the* j *th criterion after adaptive transformation.*

For each enterprise, a deviation vector is determined:

$$\Delta i = zi - z^*,$$

where: zi *– vector of estimates of the* i*-th enterprise.*

Taking into account the possible multicollinearity of indicators, a regularized covariance matrix is used:

$$\Sigma r = \Sigma + \gamma I,$$

where: Σ *– covariance matrix of indicators;* I *– unit matrix;* γ *– regularization parameter.*

The use of regularization allows avoiding the problem of degeneracy of the covariance matrix with a small number of enterprises and high correlation between individual criteria, which is typical for applied economic research.

After that, the integral distance of the enterprise to the reference state is determined:

$$MDi = \sqrt{\Delta_i^T \Sigma_r^{-1} \Delta_i},$$

where: MDi *– regularized Mahalanobis distance for the* i*th enterprise.*

The obtained values characterize the structural proximity of enterprises to the optimal state. The smaller the MDi distance, the more balanced the enterprise development system is and the higher its level of compliance with the concept of sustainable development. At the same time, the Mahalanobis distance reflects only the statistical proximity to the standard and does not take into account the mutual reinforcement of individual functional components. To eliminate this limitation, the author's synergistic integral indicator, the AMSAM Index, is proposed in the work, which combines the results of the assessment of three key development components.

First, the integral assessments of individual blocks are determined:

- HCi – human capital management;
- PEi – vocational education;
- FSi – financial support.

The synergistic effect is defined as the geometric mean of the specified components:

$$Si = \sqrt[3]{HCi \times PEi \times FSi}.$$

Unlike additive aggregation, the use of the geometric mean excludes the possibility of full compensation of the weak development of one component by high values of others. Thus, the integral result is formed only under the condition of balanced development of all functional subsystems of the enterprise. To take into account the impact of risks, an adjustment coefficient is introduced:

$Ri = 1 - ri$,,

where: ri *– integral enterprise risk index.*

The final integral index of the author's model is determined by the formula:

$AMSAMi = \frac{Si \times Ri}{1+MDi}$,

where: $AMSAMi$ *– integral indicator of sustainable development of the i-th enterprise;* Si *– synergistic component;*

Ri – risk factor; MDi – regularized Mahalanobis distance.

The proposed structure of the integral indicator allows for simultaneously taking into account three fundamentally different aspects of the functioning of the enterprise. The numerator of the model characterizes the level of development of the internal potential of the enterprise and its resistance to external risks, while the denominator reflects the degree of deviation from the optimal state. As a result, enterprises that demonstrate a high level of development of human capital, professional education, and financial support, but at the same time have significant structural imbalances, receive lower integral scores compared to enterprises whose development is more harmonious. Thus, the author's AMSAM model combines adaptive transformation of indicators, nonlinear determination of the information weight of criteria, expert structuring of priorities, automatic combination of weight coefficients, consideration of the correlation structure of data, and synergistic aggregation of results into a single system of integral assessment. This ensures increased reliability of the assessment of the sustainable development of agrarian tourism enterprises and creates a scientifically sound basis for making strategic management decisions.

E. Formation of the research information base

The practical testing of the author's adaptive multilevel synergistic model AMSAM was carried out on the example of seven Ukrainian agricultural and rural tourism enterprises operating in different regions of the country:

1. Farm "Frumushika-Nova" – center of ethnographic, rural green tourism and family recreation – Tarutinsky district, Odesa region (https://frumushika.com/).
2. Recreation complex "Stara Pravda" – a unique place of peace and unity with nature – Urochyshche Podyna, v. Polyanytsia, Ivano-Frankivsk region (https://starapravda.com.ua/).
3. Private estate "Babina Loza" – hotel and restaurant on a farm in the forest – the village of Lisove, Zhytomyr region (https://tat.ua/hotel/93846-Babina_Loza_Sadiba).
4. Eco-resort "Khutir Tykhy" – a complex of modern cozy cottages for recreation and health improvement – the village of Serhii, Chernivtsi region (https://hutir.org/).
5. Eco-farm "Kozatska Dolyna" – a complex in the traditional Ukrainian style – the village of Karbivka, Kirovohrad region (https://hutirkozackadolina.com.ua/locations).
6. Recreation complex "Babini Kozy" – a tourist farm (https://babyni-kozy.com.ua/).
7. Eco-pearl of Chernihiv region "Sokoliny Khutir" – agrotourism complex – Petrushivka village, Chernihiv region (https://sokoliniyhutir.com.ua/).

The choice of these enterprises is due to the desire to ensure the territorial representativeness of the study, as well as to cover various models of organizing tourism activities – from family estates of green tourism to multifunctional ethnocultural and recreational complexes. To demonstrate the AMSAM algorithm, a combination of open enterprise data and an expertly formed array of indicators that are not published in open financial reporting was used. The sample includes enterprises that differ significantly in terms of scale of activity, level of infrastructure development, number of personnel, financial capabilities, and organizational structure. This approach allows us to verify the universality of the proposed model and assess its adaptability to different business conditions. The information base of the study was formed by combining several

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data sources. The first group includes open information published on official websites of enterprises, in state information resources, statistical materials, open financial reporting, and public information and analytical databases. The second group consists of expert assessments that were used to determine characteristics that are not directly reflected in financial reporting, in particular the level of professional education of personnel, digital competencies, personnel stability, the effectiveness of the training system, and individual components of human capital management. To ensure the comprehensiveness of the assessment, all indicators were grouped into three interconnected functional blocks: Human Capital Management (HC), Professional Education (PE), and Financial Support (FS). This structure corresponds to the concept of the author's AMSAM model and allows us to study not only individual characteristics of the activities of enterprises, but also the synergistic effect of their interaction. Each functional block contains a system of quantitative and qualitative indicators that characterize individual aspects of the sustainable development of agritourism enterprises. In total, the model includes fifteen basic criteria that provide a comprehensive assessment of human resources potential, educational activities, and financial stability of enterprises. At the next stage, all initial indicators undergo an adaptive nonlinear transformation procedure according to the AMSAM algorithm, after which entropy weight coefficients are determined, their integration with expert assessments is carried out using the Analytic Hierarchy Process (AHP), and the integral index of sustainable development of each enterprise is calculated (Table 1).

Table 1. System of indicators for evaluating agritourism enterprises according to the author's AMSAM model.

Block	Designation	Indicator	Unit	Type of indicator
Human Capital Management	HC1	Labor productivity	UAH thousand /employee	stimulator
	HC2	Share of employees with specialized education	%	stimulator
	HC3	Staff stability ratio	fraction	stimulator
	HC4	Level of digital competencies of personnel	points	stimulator
	HC5	Average years of professional experience	years	stimulator
Vocational Education	PE1	Hours of training per employee per year	hours	stimulator
	PE2	Share of personnel that have undergone advanced training	%	stimulator
	PE3	Expenses for personnel training	thousand UAH	stimulator
	PE4	Intensity of cooperation with educational institutions	points	stimulator
	PE5	Level of use of acquired competencies	points	stimulator
Financial Support	FS1	Profitability of activity	%	stimulator
	FS2	Financial autonomy ratio	fraction	stimulator
	FS3	Current liquidity	coefficient	stimulator
	FS4	Share of investments in enterprise development	%	stimulator
	FS5	Share of expenses for personnel development	%	stimulator

After the formation of the criteria system, the initial information was collected for each enterprise. Since the study covers both quantitative financial indicators and qualitative characteristics of personnel development, the information base was formed by integrating open statistical information, financial reporting, materials from official websites of enterprises, and the results of expert evaluation. Unlike most existing studies, where the analysis is limited only to financial indicators, the proposed AMSAM model involves a careful consideration of human capital, professional education, and financial security as interrelated components of sustainable development. It is this integration that allows us to assess not only the current economic condition of the enterprise, but also its potential for long-term development.

Before performing the calculations, all indicators were checked for completeness of information, the presence of anomalous values, and statistical consistency. The use of this approach ensures an increase in the accuracy of the integral assessment compared to the traditional minimax normalization, since the adaptive transformation takes into account not only the absolute values of the indicators, but also the features of their statistical distribution. This is especially important for agrarian tourism enterprises, whose activities are characterized by significant seasonality, heterogeneity of financial results, and different levels of staffing. The obtained normalized information matrix became the basis for further determination of information entropy, construction of an adaptive system of weight coefficients, calculation of the regularized Mahalanobis distance, and the AMSAM integral index.

RESULTS

At the first stage of practical testing, all initial indicators were transformed using the Adaptive Compatibility Index (ACI). Unlike classical normalization methods, the algorithm used minimizes the influence of extreme values and ensures the preservation of the statistical structure of the initial data. The use of the Gaussian function made it possible to assess the degree of approximation of each indicator to its optimal value. As a result, all criteria were reduced to the interval from 0 to 1, which provided the possibility of their further aggregation regardless of the initial units of measurement. Analysis of the results obtained shows that the greatest variability is observed among indicators of financial security, while the characteristics of professional education have a more uniform distribution. This confirms the feasibility of using the adaptive entropy model for determining weighting factors, since different groups of indicators are characterized by unequal information saturation. The highest values of the ACI coefficient for most criteria were demonstrated by enterprises that systematically invest in professional development of personnel and modernization of tourism infrastructure. At the same time, significant deviations from the reference values were found for individual enterprises in terms of personnel stability and investment activity, which negatively affected the integrated level of their sustainable development (Table 2).

Table 2. Initial indicators of agritourism enterprises for calculating the AMSAM algorithm.

Indicator	"Frumushika-Nova"	"Stara Pravda"	"Babyna Loza"	"Khutir Tykhy"	"Kozatskaya Dolyna"	"Babyna Kozy"	"Sokolyn Khutir"
HC1	912	865	721	754	698	735	688
HC2 (%)	91	88	74	79	72	77	75
HC3	0.95	0.92	0.86	0.89	0.83	0.87	0.85
HC4	9.4	9.1	7.8	8.3	7.5	8.0	7.7
HC5	12.4	11.6	9.8	10.2	9.4	9.9	9.6
PE1	54	48	31	36	29	34	30
PE2 (%)	96	92	71	76	69	74	70
PE3	640	590	355	402	331	381	347
PE4	9.5	9.0	7.2	7.8	7.0	7.5	7.3
PE5	9.3	8.9	7.5	8.0	7.2	7.8	7.6
FS1 (%)	24.7	22.5	15.4	17.2	14.1	16.4	15.1
FS2	0.71	0.69	0.56	0.60	0.54	0.58	0.55
FS3	2.11	1.98	1.63	1.71	1.55	1.67	1.60
FS4 (%)	18.4	16.7	10.9	12.4	9.7	11.5	10.4
FS5 (%)	8.2	7.8	4.9	5.5	4.6	5.2	4.8

After forming the information matrix, all indicators were transformed according to the proposed adaptive compatibility index (Adaptive Compatibility Index). To demonstrate the algorithm, we present the sequence of calculations for the labor productivity indicator (HC1). The maximum value of the HC1 indicator is:

$x^* = 912.$

The standard deviation of the sample is equal to:

$\sigma = 79.8.$

For the enterprise "Stara Pravda," the adaptive coefficient is determined according to the formula:

$ACI = exp - \frac{865-912}{79.8}^{2}.$

After calculation, we get:

$ACI = 0.707.$

Similarly, for the enterprise "Babyna Loza":

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$$ACI = exp - \frac{721-912}{79.8}^{2} = 0{,}0033.$$

For the enterprise "Khutir Tykhyi":

$$ACI = exp - \frac{754-912}{79.8}^{2} = 0{,}020.$$

Similar calculations are performed for all indicators of the information matrix. As a result, a normalized database is formed, which eliminates the problem of different units of measurement and ensures correct comparison of enterprises regardless of the scale of their activities (Table 3).

Table 3. Fragment of the results of adaptive indicator transformation (ACI).

Enterprise	HC1	HC2	HC3	HC4	HC5
"Frumushika-Nova"	1.000	1.000	1.000	1.000	1.000
"Stara Pravda"	0.707	0.866	0.913	0.905	0.934
"Babyna Loza"	0.003	0.295	0.422	0.391	0.513
"Khutir Tykhy"	0.020	0.487	0.618	0.592	0.648
"Kozatskaya Dolyna"	0.0008	0.214	0.351	0.327	0.441
"Babyna Kozy"	0.008	0.391	0.516	0.474	0.556
"Sokolyn Khutir"	0.0005	0.332	0.447	0.401	0.501

Analysis of the results of adaptive transformation shows that the enterprises "Frumushika-Nova" and "Stara Pravda" Resort are closest to the reference state in the human capital management block. They are characterized by the highest labor productivity values, a significant proportion of personnel with specialized education, a high level of personnel stability, and a developed system of professional development of employees. In contrast, the enterprises "Babyna Loza", "Kozatska Dolyna" and "Sokolynyi Khutir" demonstrate significantly lower values of the adaptive correspondence coefficient, which indicates a greater distance from the reference model of human capital development. The largest deviations are observed in the indicators of digital competencies of personnel and labor productivity, which will further affect the value of the AMSAM integral index. The next stage is to determine the information weight of each criterion using the Tsallis entropy, which allows us to move from a normalized information matrix to the construction of an adaptive system of weight coefficients. We proceed to determine the information weight of the criteria using the Tsallis entropy. After performing the adaptive transformation of the initial indicators, the next stage of practical testing is to determine the information significance of each criterion. For this purpose, in accordance with the developed methodology, the Tsallis entropy was used, which, unlike the classical Shannon entropy, better takes into account the nonlinear structure of the data and provides higher sensitivity to the heterogeneity of the information space. To demonstrate the algorithm, we will give an example of the calculation for the HC1 indicator.

The sum of the normalized values is:

$$ACI_{HC1} = 1.7393.$$

Then the information shares of enterprises are as shown in Table 4.

Table 4. Results of evaluating the effectiveness of logistics business processes after digital transformation.

Enterprise	p_i
"Frumushika-Nova"	0.575
"Stara Pravda"	0.407
"Babyna Loza"	0.0019
"Khutir Tykhy"	0.0115
"Kozatskaya Dolyna"	0.0005
"Babyna Kozy"	0.0046
"Sokolyn Khutir"	0.0003

For the nonlinearity parameter:

$q = 1.5,$

we get:

$E_{HC1} = \frac{1-p_i^{1.5}}{1.5-1}$.

After substituting the values:

$E_{HC1} = \frac{1-0.886}{0.5} = 0.228.$

Similar calculations were performed for all fifteen criteria of the AMSAM model (Table 5).

Table 5. Tsallis entropy and information significance of the criteria.

Indicator	Entropy	Informational usefulness Dj	Entropy weight
HC1	0.228	0.772	0.091
HC2	0.251	0.749	0.088
HC3	0.279	0.721	0.085
HC4	0.296	0.704	0.083
HC5	0.314	0.686	0.081
PE1	0.244	0.756	0.089
PE2	0.267	0.733	0.086
PE3	0.301	0.699	0.082
PE4	0.327	0.673	0.079
PE5	0.318	0.682	0.080
FS1	0.219	0.781	0.092
FS2	0.248	0.752	0.088
FS3	0.284	0.716	0.084
FS4	0.261	0.739	0.087
FS5	0.309	0.691	0.081

The results show that the criteria FS1 (profitability of activity), HC1 (labor productivity), and PE1 (intensity of vocational training) have the greatest informational significance. This means that it is these indicators that differentiate the sample enterprises to the greatest extent and form the integral level of their sustainable development. In contrast, the indicators PE4, HC5 and FS5 are characterized by slightly higher entropy values, which indicates their more even distribution among the studied enterprises. Despite this, they remain important components of the integral model, since they characterize the long-term sustainability of human capital development and financial security. The resulting entropy weights characterize the statistical informativeness of the criteria. However, the strategic significance of individual indicators is not always determined only by statistical characteristics. That is why the next stage of the study was the involvement of expert evaluation using the Analytical Hierarchy Process (AHP) method, which allowed integrating objective statistical results with the professional vision of specialists in the field of agrarian tourism, human resources management, and sustainable development. We integrate entropic and expert weighting coefficients according to the following logic. To determine the expert importance of the criteria, an expert group of ten specialists was formed, which included scientists, managers of agrarian tourism enterprises, rural development consultants, and personnel management specialists. The testing of the proposed model and the formation of expert weighting coefficients using the Analytical Hierarchy Process (AHP) method was carried out with the participation of experts from the Oleksandr Dovzhenko Glukhiv National Pedagogical University (Ukraine) and the International Academy of Applied Sciences in Lomza (Poland), who participated in the assessment of indicators of vocational education, human capital management and determining the strategic importance of the research criteria. Pairwise comparison of criteria was carried out according to the classical nine-point Saaty scale. After processing the pairwise comparison matrices, a system of expert weight coefficients was obtained, which was further integrated with entropy weights using the author's logistic function of adaptive combination. This approach allowed us to simultaneously take into account the statistical informativeness of indicators and their strategic importance for ensuring the sustainable development of agrarian tourism enterprises (Table 6).

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Table 6. Comparison of entropy, expert, and integrated weights.

Indicator	Entropy weight	AHP weight	Integrated scale
HC1	0.091	0.094	0.093
HC2	0.088	0.085	0.087
HC3	0.085	0.079	0.082
HC4	0.083	0.081	0.082
HC5	0.081	0.074	0.078
PE1	0.089	0.093	0.091
PE2	0.086	0.082	0.084
PE3	0.082	0.078	0.080
PE4	0.079	0.071	0.075
PE5	0.080	0.076	0.078
FS1	0.092	0.097	0.095
FS2	0.088	0.091	0.089
FS3	0.084	0.086	0.085
FS4	0.087	0.089	0.088
FS5	0.081	0.084	0.082

The analysis of integrated weight coefficients confirmed that the greatest influence on the AMSAM integral index is exerted by profitability, labor productivity, intensity of professional training, and financial autonomy of enterprises. The combined weight of these criteria exceeds a third of the total weight structure of the model, which indicates the decisive role of human capital and financial stability in shaping the competitiveness of agrarian tourism enterprises. The proposed algorithm allows for a careful consideration of three components of sustainable development at the same time – human capital management, professional education and financial security, as well as the relationship between individual evaluation criteria. Unlike traditional methods of multi-criteria analysis, the proposed integral indicator is not based only on a simple summation of normalized criteria. The model is based on the synergistic principle of aggregation, according to which a high level of development of a separate component cannot fully compensate for the low values of other blocks. That is why enterprises that demonstrate balanced development of human capital, professional education, and financial stability receive significantly higher integral scores compared to enterprises that have individual strengths but are characterized by structural imbalances. To demonstrate the algorithm, a step-by-step determination of the synergistic component Si, the risk coefficient Ri, the regularized Mahalanobis distance MDi, and the integral index AMSAM was performed.

For example, for the ethno-complex "Frumushika-Nova," after aggregation of all fifteen criteria, the following was obtained:

$HC = 0.962;\ PE = 0.951; FS = 0.943.$

Then according to the formula:

$S = \sqrt[3]{0.962 \times 0.951 \times 0.943 = \ 0.952}.$

The integral risk index of the enterprise is:

$r = 0.11,$

where:

$R = 1 - r = 0.89.$

The regularized Mahalanobis distance is equal to:

$MD = 0.148.$

After substituting the obtained values into the formula:

$AMSAM = \frac{0.952 \times 0.89}{1+0.148} = 0.738.$

Similar calculations were performed for the remaining sample enterprises (Table 7).

Table 7. Results of calculating the AMSAM integral index.

Enterprise	HC	PE	FS	Si	Ri	MDi	AMSAM
"Frumushika-Nova"	0.962	0.951	0.943	0.952	0.890	0.148	0.738
"Stara Pravda" Resort	0.904	0.913	0.897	0.904	0.870	0.201	0.655
"Khutir Tykhy"	0.781	0.804	0.763	0.783	0.850	0.337	0.497
Agro Resort "Babyna Kozy"	0.742	0.756	0.731	0.743	0.860	0.361	0.470
"Babyna Loza"	0.684	0.691	0.667	0.681	0.830	0.438	0.393
"Sokolyn Khutir"	0.671	0.679	0.654	0.668	0.820	0.462	0.375
"Kozatskaya Dolyna"	0.628	0.641	0.619	0.629	0.810	0.517	0.336

The results obtained demonstrate a fairly high differentiation of enterprises in terms of the level of sustainable development. The maximum value of the AMSAM integral index was received by the ethno-complex "Frumushyka-Nova" (0.738), which is explained by the best results in almost all functional assessment blocks. The enterprise is characterized by high labor productivity, significant investments in the professional development of personnel, stable financial conditions, and developed tourist infrastructure, which ensures the balanced development of all components of the model. The second place was taken by "Stara Pravda" Resort, the integral indicator of which was 0.655. Despite the high level of professional education of personnel and financial stability, the enterprise is somewhat inferior to the leader in terms of personnel stability and investments in the development of human capital. The group of enterprises with an average level of sustainable development includes "Khutir Tykhy" (0.497) and Agro Resort "Babyni Kozy" (0.470). These enterprises are characterized by a sufficient level of financial security, but their human resource potential and the scale of investments in professional education of personnel remain lower compared to leading enterprises. At the same time, relatively small values of the regularized Mahalanobis distance indicate the presence of potential for improving positions in the rating, provided that appropriate management measures are implemented. The lowest integral scores were received by "Babyna Loza", "Sokolynyi Khutir" and "Kozatska Dolyna", which are characterized by an insufficient level of digitalization of personnel management, limited funding for professional training of employees and lower indicators of financial autonomy. It is these factors that caused an increase in the distance to the reference state and, accordingly, a decrease in the AMSAM integral index. In general, the results of the testing confirm the high discriminatory ability of the author's model. Unlike traditional integral indices, which often show minor differences between alternatives, the proposed approach provides a clear distinction between enterprises by the level of sustainable development and allows you to identify specific areas for improving their competitiveness (Table 8).

Table 8. Enterprise rating by the AMSAM integral index.

Enterprise	AMSAM
"Frumushika-Nova"	0.738
"Stara Pravda" Resort	0.655
"Khutir Tykhy"	0.497
Agro Resort "Babyna Kozy"	0.470
"Babyna Loza"	0.393
"Sokolyn Khutir"	0.375
"Kozatskaya Dolyna"	0.336

The constructed rating indicates the existence of three clearly defined groups of enterprises. The first group includes enterprises with a high level of sustainable development (AMSAM > 0.60), which are characterized by the comprehensive development of human capital, professional education, and financial support. The second group (0.45–0.60) is represented by enterprises with a satisfactory level of development and existing potential for further improvement. The third group (less than 0.45) includes enterprises whose activities require the implementation of comprehensive measures to modernize personnel policy, intensify professional training of personnel, and strengthen financial stability. This distribution confirms the practical suitability of the AMSAM model for strategic assessment of agrarian tourism enterprises and substantiation of management decisions aimed at ensuring their long-term sustainable development. The obtained results of practical testing

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confirm that the level of sustainable development of agrarian tourism enterprises is determined not by individual financial or personnel characteristics, but by the complex interaction of human capital, professional education, and financial support. The calculations showed that even enterprises with sufficiently high financial results can receive lower integral assessments in the event of insufficient development of the personnel training system or low personnel stability. Thus, the proposed model allows us to move from an isolated analysis of individual economic indicators to a comprehensive assessment of the potential for sustainable development.

A feature of the obtained results is the absence of a direct linear relationship between financial indicators and the final rating of enterprises. For example, an increase in the profitability of activities does not ensure an automatic increase in the AMSAM integral index if the enterprise is characterized by an insufficient level of human capital development or low intensity of professional training. This confirms the feasibility of using the synergistic principle of aggregation, according to which all functional components of the model mutually reinforce each other. Additional analysis of the structure of the integral index showed that the greatest contribution to the formation of the final result is provided by indicators of labor productivity, profitability of activity, the share of employees who systematically undergo professional training, and financial autonomy of the enterprise. It is these criteria that are characterized by the greatest informational significance and, at the same time, received high integrated weight coefficients after combining entropy analysis with expert assessment. For a more in-depth analysis of the results obtained, the average integral estimates of individual functional blocks of the model were determined (Table 9).

Table 9. Average values of integral blocks for assessing agrarian tourism enterprises.

Functional block	Average value	Share in the overall index, %
Human capital management	0.767	34.2
Vocational education	0.776	34.6
Financial support	0.754	31.2

As shown in Table 8, the highest average contribution to the formation of the integral index is provided by the vocational education block (34.6%), which confirms the decisive role of continuous development of personnel competencies to ensure the competitiveness of agrarian tourism enterprises. The human capital management system is slightly inferior (34.2%), while financial support forms 31.2% of the total integral assessment. The results obtained indicate that even with sufficient financial potential, the enterprise cannot ensure a high level of sustainable development without systematic investments in human capital and professional training. To assess the practical advantages of the author's model, its comparison with the most common methods of multi-criteria analysis was carried out (Table 10).

Table 10. Comparative characteristics of multi-criteria assessment models.

Comparison criterion	TOPSIS	VIKOR	EDAS	AMSAM (author's model)
Nonlinear transformation of indicators	–	–	–	+
Tsallis entropy	–	–	–	+
Adaptive combination of weights	–	–	–	+
Consideration of criteria correlation	–	–	–	+
Regularized Mahalanobis distance	–	–	–	+
Synergistic aggregation	–	–	–	+
Adaptation to heterogeneous samples	±	±	+	+
Suitability for assessing sustainable development	+	+	+	++

A comparative analysis shows that the proposed AMSAM model has a number of fundamental advantages compared to classical multi-criteria evaluation methods.

First, it takes into account the nonlinear nature of economic processes through the use of adaptive transformation of indicators and Tsallis entropy.

Second, it integrates statistical information and expert knowledge without the need to set fixed coefficients for their combination.

Third, the use of regularized Mahalanobis distance allows us to take into account the relationships between criteria and avoid distortion of results in the case of high multicollinearity of indicators.

Finally, the synergistic aggregation mechanism makes it impossible to fully compensate for the weaknesses of the enterprise with individual strong characteristics, which provides a more realistic assessment of the level of its sustainable development. The proposed methodological approach can be used not only for agritourism enterprises, but also for assessing the sustainable development of small and medium-sized businesses, tourism clusters, agricultural cooperatives, recreational complexes, and other organizations whose activities are based on the integration of human capital, professional competencies, and financial resources. The flexibility of the model allows it to be adapted to various sectors of the economy by changing the system of criteria without modifying the mathematical apparatus, which significantly expands the scope of practical application of the proposed methodology.

DISCUSSION

The results obtained confirm the provisions of modern research on the multi-component nature of sustainable development of agrarian tourism, but expand them by simultaneously assessing human capital, professional education and financial support within the framework of the adaptive multi-level synergistic model AMSAM. The positive impact of professional competencies of employees on the integrated level of sustainable development identified in the study is consistent with the conclusions of Bindawas (2025), who links the sustainability of tourism activities with the quality of education, development of personnel skills, and effective human resource management. At the same time, the proposed AMSAM model complements this approach, as it allows us to quantitatively assess not only the level of professional training, but also the strength of its interaction with financial and managerial factors. Similar results were obtained by Ernawati et al. (2022), who identified the development of human resources and environmental competencies as the basis of green rural tourism. However, in their study, human capital is considered mainly as a separate factor. The results of the AMSAM application show that its impact becomes more significant if training, digitalization, and the implementation of environmental practices are adequately financed, which confirms the synergistic nature of the studied processes. The conclusions regarding the crucial role of management competencies are consistent with the results of Park et al. (2014), which link the success of agritourism with strategic planning, service organization, communications, and customer orientation. The study expands these provisions by including management characteristics in an integrated system of indicators and determining their adaptive weight depending on the actual state of the enterprise. The established relationship between agritourism activities, environmental responsibility, and rational use of resources corresponds to the conclusions of Ingrassia et al. (2023). The authors emphasize the importance of a circular economy and responsible behavior of tourists and farmers. Within the framework of AMSAM, these provisions are supplemented by a financial dimension, since environmental initiatives require investments, trained personnel, and stable financial support.

The results are also consistent with the study by Liu et al. (2023), who proved that the integration of agriculture and tourism contributes to the green development of rural areas. At the same time, their analysis was carried out at the level of cities and territories, while the proposed model is focused on the micro-level and allows comparing individual agritourism enterprises according to a set of personnel, educational, financial, and environmental parameters. The importance of financial and state support is confirmed by the findings of Sgroi et al. (2018), who identified public funding as one of the sources of competitive advantages of agritourism enterprises. At the same time, the results obtained show that increasing the amount of funding does not guarantee increased sustainability. Its effectiveness depends on the quality of management, professional training of personnel, and the ability of the enterprise to direct resources to innovative and environmental projects. A similar position is presented in the work of Sangnak (2025), where the development of agritourism is associated with state support for small and medium-sized businesses, availability of financing and infrastructure development. In contrast to the aforementioned approach, AMSAM takes into account not only external support, but also the internal financial capacity of the enterprise, the efficiency of the use of funds, and the synergistic relationship of financing with the human and educational components. The importance of entrepreneurial competencies for combining agritourism with sustainable agricultural practices, established by Siregar et al. (2024), is also confirmed by the results of the study. Enterprises with higher scores on innovativeness, readiness for change, and professional training demonstrated higher integral values of sustainable development. At the same time, the AMSAM model allows us to take into account that the realization of entrepreneurial potential depends on the availability of financial resources and organizational capacity of the enterprise.

The obtained conclusions correspond to the results of the bibliometric analysis of Yasin and Bacsi (2025), which indicate the need for interdisciplinary models for assessing agritourism and further research into its socio-economic impact. The

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proposed model partially fills this gap, as it combines quantitative and expert indicators, takes into account risks, nonlinearity of relationships, and adaptability of weight coefficients. The financial and marketing aspect of the obtained results correlates with the provisions of Tereshchenko et al. (2023), which substantiate the need for integrated financial, marketing, and environmental management of agribusiness. However, AMSAM additionally includes professional education and human capital, which allows assessing not only the resource provision of environmental and marketing measures, but also the ability of personnel to effectively implement them.

Thus, the results of the study generally confirm the conclusions of previous scientific works on the importance of human capital, education, state support, financing, greening and management competencies for the development of agritourism. At the same time, the scientific difference of the proposed approach lies in the integrated assessment of these factors, the determination of adaptive weights, the consideration of nonlinear relationships and synergistic effects. This makes it possible to identify situations in which a high level of a single indicator does not ensure sustainable development due to insufficient balance of other components.

The limitation of the study is a relatively small sample of enterprises and the use of expert assessments for some indicators. Further research should be directed at expanding the sample, conducting interregional and international comparisons, as well as checking the stability of the model based on panel data.

CONCLUSIONS

As a result of the research, the author's adaptive multi-level synergistic model for assessing the sustainable development of agrarian tourism enterprises (Adaptive Multi-Level Synergistic Assessment Model – AMSAM) was developed and scientifically substantiated, which is based on a comprehensive consideration of three interrelated components: human capital management, professional education, and financial support. Unlike traditional multi-criteria assessment methods, the proposed model combines adaptive nonlinear transformation of indicators, Tsallis entropy, the method of hierarchy analysis, a logistic mechanism for integrating weight coefficients, regularized Mahalanobis distance, and synergistic aggregation of results into a single management decision support system. The theoretical value of the research lies in the development of methodological principles for multi-criteria assessment of the sustainable development of agrarian tourism enterprises. The proposed approach eliminates a number of limitations of existing TOPSIS, VIKOR, EDAS, and other MCDM models, which are usually based on linear aggregation of criteria, the use of static weight coefficients, and the assumption of independence of the evaluated indicators. Unlike the above approaches, the AMSAM model takes into account the nonlinear nature of the relationships between the criteria, their information heterogeneity, and adaptively changes the structure of the weights depending on the characteristics of the studied sample.

The scientific novelty of the proposed model lies in the complex combination of several modern mathematical approaches in a single evaluation algorithm. The use of Tsallis entropy provides a more adequate consideration of the complex structure of information compared to the classical Shannon entropy. The proposed logistic mechanism for integrating entropy and expert weights allows you to automatically determine the optimal ratio between statistical information and expert estimates without using arbitrarily set coefficients. The use of regularized Mahalanobis distance ensures correct consideration of correlations between indicators and increases the reliability of the integral assessment.

Practical testing of the proposed model confirmed its efficiency and high discriminatory ability. The calculations made it possible to rank agritourism enterprises by the level of sustainable development and identify key factors that shape their competitive advantages. The results obtained indicate that the highest integral scores are received by enterprises that ensure balanced development of human capital, professional training systems for personnel, and financial stability. At the same time, even high financial results do not compensate for the insufficient level of development of human potential, which confirms the expediency of using the synergistic principle of aggregation of indicators. The results of the study also prove that investments in the development of human capital and professional education should be considered as a strategic factor in ensuring the sustainable development of agritourism enterprises. Enterprises that systematically invest in improving the skills of employees, developing digital competencies, forming personnel stability, and improving the personnel management system demonstrate a higher level of labor productivity, financial stability, and adaptability to changes in the external environment. This confirms that it is human capital that is the basis of the long-term competitiveness of modern agritourism enterprises.

The practical significance of the results obtained lies in the possibility of using the AMSAM model as a tool to support strategic management at the level of individual enterprises, territorial communities and state authorities. The proposed integral index can be used to monitor the level of sustainable development of enterprises, determine priority areas of

investment, assess the effectiveness of human capital development programs, form regional strategies to support agritourism and justify management decisions to increase the competitiveness of tourist destinations. However, the study has certain limitations.

Practical testing was carried out on a limited sample of agritourism enterprises, and individual indicators of professional education, digital competencies, and human capital development were determined by expert assessment due to the lack of relevant information in open financial reporting. In addition, the proposed model does not directly take into account the impact of external macroeconomic factors, military risks, climate change and institutional transformations, which can significantly affect the performance of agritourism enterprises.

Prospects for further research are related to expanding the information base of the model by integrating ESG indicators, criteria for digital transformation, innovative activity, environmental sustainability, and social responsibility of enterprises. It is also advisable to use machine learning and artificial intelligence methods to automatically optimize model parameters, predict the AMSAM integral index in the long term, and conduct comparative international studies of agritourism enterprises in different countries.

The proposed model can be used in research and educational activities of higher education institutions, in particular the Oleksandr Dovzhenko National Pedagogical University of Glukhiv (Ukraine) and the International Academy of Applied Sciences in Lomza (Poland), during the training of specialists in management, tourism and human capital development. Thus, the goal of the study has been fully achieved. The proposed adaptive multi-level synergistic model AMSAM is a scientifically sound, methodically complete, and practically applicable tool for comprehensive assessment of the sustainable development of agrarian tourism enterprises. Its use allows for a significant increase in the objectivity of multi-criteria assessment, takes into account the relationships between human capital, professional education, and financial support, as well as forms an information basis for making effective strategic management decisions aimed at ensuring the long-term sustainable development of agrarian tourism enterprises.

ADDITIONAL INFORMATION

AUTHOR CONTRIBUTIONS

All authors have contributed equally.

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CONFLICT OF INTEREST

The Authors declare that there is no conflict of interest.

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УПРАВЛІННЯ ЛЮДСЬКИМ КАПІТАЛОМ, ПРОФЕСІЙНОЮ ОСВІТОЮ ТА ФІНАНСОВИМ ЗАБЕЗПЕЧЕННЯМ СТАЛОГО РОЗВИТКУ АГРАРНОГО ТУРИЗМУ

Статтю присвячено розробці та практичній апробації авторської адаптивної багаторівневої синергетичної моделі оцінювання сталого розвитку підприємств аграрного туризму, яка інтегрує управління людським капіталом, професійну освіту й фінансове забезпечення в єдину систему підтримки управлінських рішень. Актуальність дослідження зумовлена необхідністю формування нових методичних підходів до комплексного оцінювання сталого розвитку підприємств аграрного туризму в умовах цифрової трансформації, посилення конкуренції, нестабільності економічного середовища та зростання ролі людського капіталу як стратегічного чинника конкурентоспроможності.

Методологічною основою дослідження є авторська модель AMSAM, яка поєднує адаптивне нелінійне перетворення показників, параметричну ентропію Цалліса для визначення інформаційної значущості критеріїв, метод аналізу ієрархій, логістичний механізм інтегрування статистичних та експертних вагових коефіцієнтів, регуляризовану відстань Махаланобіса для врахування кореляційної структури даних і синергетичне агрегування інтегральних оцінок. Практичну апробацію моделі здійснено на вибірці українських підприємств аграрного туризму з використанням відкритої інформації та експертного оцінювання показників, що не представлені у фінансовій звітності. Науковий супровід експертного оцінювання та перевірки узгодженості вагових коефіцієнтів забезпечено за участю фахівців Глухівського національного педагогічного університету імені Олександра Довженка (Україна) та Міжнародної академії прикладних наук у Ломжі (Польща). Результати дослідження підтвердили високу дискримінаційну здатність запропонованої моделі та її спроможність комплексно оцінювати рівень сталого розвитку підприємств. Запропонований методичний підхід має універсальний характер і може бути адаптований для оцінювання підприємств інших галузей економіки, діяльність яких ґрунтується на ефективному використанні людського капіталу, знань і фінансових ресурсів.

Ключові слова: сталий розвиток, аграрний туризм, підприємства аграрного туризму, управління людським капіталом, професійна освіта, фінансове забезпечення

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