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RESEARCH ARTICLE

Developing Meta-Preventive Competence in Medical Education Via Reflexive-Preventive Modeling, Mathematical and Statistical Validation

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Abstract

The formation of preventive thinking and hygienic-analytical skills is a priority of modern medical education; however, pedagogical frameworks specifically aimed at developing students' metapreventive competence remain insufficiently elaborated. This study aimed to develop, implement, and statistically validate a model and methodology for developing preventive medicine students' metapreventive competence through Reflexive-Preventive Modeling Technology (RPMT) in the teaching of occupational hygiene. A combination of theoretical (analytical-synthetic, comparative, modeling), diagnostic (surveys, testing, observation), prognostic (expert evaluation), pedagogical-experimental, and mathematical-statistical methods was employed. A multi-center pedagogical experiment was conducted in 2022–2025 at three medical higher education institutions of Uzbekistan (Fergana, Andijan, and Urgench), involving 465 preventive medicine students. The methodology integrated interactive modeling, problem-based analysis of hygienic situations, and collaborative sanitary-expert discussions. Pearson's chi-squared test ($\alpha = 0.05$; $\chi^2_{crit} = 5.99$) was used for statistical validation.

KEYWORDS

Occupational health, industrial hygiene, risk assessment, preventive thinking, competency-based approach, metapreventive competence.

INTRODUCTION

Healthcare and hygiene placements in medical education contribute significantly to student learning and the acquisition of preventive skills. Exploring students' self-conceptualization of these practices may provide insights to better support modern medical training [16]. The theoretical foundations of experience-based training, competency-based approaches, and interactive methods in medical education have been extensively explored by foreign researchers, including David Boud, Stephen Billett, Ronald Barnett, John Biggs, Patricia Cantillon, and Michael Eraut. However, comprehensive pedagogical frameworks specifically aimed at developing the metapreventive competence of students through the integration of reflexive analysis, preventive thinking, and modeling technologies remain insufficiently developed.

To address this gap, the innovative didactic potentials of developing students' metapreventive competence in medical education need to be clarified based on the mutual integration of cognitive-prognostic perception of workplace hazards, anticipatory assessment of sanitary risks, and reflexive analysis of preventive decisions. Therefore, this study aims to enhance the model and methodology for developing students' metapreventive competence within the occupational hygiene curriculum, dynamically intensifying preventive-analytical skill development and optimizing diagnostic criteria for evaluation.

METHODS

A teaching-methodical model based on Reflexive-Preventive Modeling Technology (RPMT) aimed at developing students' metapreventive competence was developed and successfully implemented into the practical training process of occupational hygiene [9–12, 14].

To support this framework, a complex of methodical materials, including interactive learning tasks, hygienic situational cases, and preventive modeling assignments, was created to enable students to identify environmental hazards and analyze sanitary risks. Concurrently, a system of practical training algorithms and methodological recommendations focused on risk assessment, sanitary determinant identification, and preventive strategy formulation was established.

Diagnostic criteria, indicators, and evaluation tools were formulated to measure the levels of students' hygienic-analytical thinking, preventive decision-making, and metahygienic reflection. Empirical results verified that the developed methodology significantly enhances students' competencies in systemic risk factor analysis, prognostic risk assessment, and well-founded preventive decision-making.

Research Design and Implementation Phases. The pedagogical experiment was executed in distinct chronological phases to evaluate the efficacy of the Reflexive-Preventive Modeling Technology (RPMT) in developing students' metapreventive competence.

The Main (Interventional) Phase: This stage served as the core of the experimental work, where the developed methodology was directly integrated into the educational process. In the experimental groups, the teaching of occupational hygiene was structured entirely around the RPMT framework. Educational sessions utilized interactive tasks including the modeling of hygienic scenarios, occupational risk assessments, and the formulation of scientifically grounded preventive strategies. Problem-based case studies directly addressed key industrial hygiene factors, such as occupational noise, industrial dust, hazardous chemical exposures, and microclimate variables. Within these cases, students were tasked with identifying specific hazards, evaluating their compliance with sanitary regulations, and interpreting their physiological impacts on human health. The Modeling and Evaluation Component: During the modeling stages of the RPMT framework, students designed preventive models recommending technical, organizational, and individual protective measures (PPE). The instructional methods relied on group discussions, situational analysis, the interpretation of sanitary monitoring datasets, and peer-led reflexive evaluation. Conversely, the control groups followed traditional teaching methods, providing a baseline for comparative analysis.

Multi-Center and Environmental Context. To evaluate the universality, scalability, and structural stability of the RPMT methodology, the experiment was deployed across geographically and organizationally diverse higher education institutions. A multi-center pedagogical experiment was conducted between 2022 and 2025 across three medical institutions in Uzbekistan (Fergana, Andijan, and Urgench), involving a total of 465 preventive medicine students. These institutions exhibited variations in student demographics, faculty teaching experience, and material-technical resources. This multi-center approach allowed for a rigorous comparative analysis of how the methodology operates under varying educational environments and infrastructures, ensuring that the acquired data reflects systemic adaptability rather than localized variables.

Assessment Criteria and Statistical Validation. In the final (analytical) phase, the empirical data gathered throughout the interventional period was systematized for statistical processing. The dynamic progression of students' metapreventive competence was monitored by comparing post-intervention performance metrics with baseline diagnostic data. The structural evaluation relied on four primary diagnostic criteria:

-The precision of diagnosing simulated hygienic situations.

-The response velocity in identifying sanitary-hygienic risks.

-The scientific and regulatory validity of proposed preventive decisions.

-The degree of student autonomy during independent analytical tasks.

Every educational session concluded with a structured reflexive feedback loop, acting as a qualitative assessment metric where students critically reviewed their tactical approaches against national sanitary-hygienic standards and industrial safety codes. Faculty members transitioned into a moderation role during these loops to evaluate the scientific validity of student-designed models.

To verify the significance of the variations observed between the experimental and control cohorts, mathematical-statistical analysis (including pre- and post-test comparative distributions) was applied to validate the pedagogical efficiency of the framework. The baseline and post-interventional competencies were evaluated across motivational, cognitive, and activity-based criteria. The statistical validity of the empirical data was rigorously verified using Pearson's chi-squared ($\chi 2$) test at a significance level of = 0.05 ($K = 2$, $\chi 2\_crit = 5.99$).

RESULTS AND DISCUSSION

The analysis of the content of the methodology for developing students' metapreventive competence using RPMT (Reflexive-Preventive Modeling Technology) technologies shows that this process is not limited to the assimilation of theoretical hygienic knowledge. Rather, it encompasses an integrative pedagogical activity aimed at the systemic analysis of sanitary-risk factors in the workplace, the identification of hygienic determinants, and the scientifically grounded formulation of preventive decisions. In this methodology, the processes of reflexive analysis, preventive thinking, hygienic modeling, and the application of sanitary technologies are organized in a harmonized manner, serving to gradually develop students' hygienic thinking and analytical competencies. This approach forms skills in identifying hazardous factors in the industrial environment, interpreting sanitary monitoring results, and developing preventive measures aimed at ensuring healthy working conditions. Consequently, readiness for sanitary-preventive activities, hygienic diagnostics, and metapreventive competence regarding the prognostic assessment of occupational risk factors are systematically developed in students [1].

Target and Content Components of the Methodology Firstly, the target and content structure of the methodology manifests as a complex pedagogical system aimed at forming students' metapreventive competence. The primary goal of this system is to shape students into specialists ready to identify hygienic factors in the production environment, scientifically analyze sanitary determinants, and prognostically evaluate occupational risk factors. From this perspective, the content of the methodology is based on the mutual integration of hygienic knowledge, sanitary-analytical skills, and preventive decision-making activities. The content structure includes the theoretical foundations of occupational hygiene alongside elements of practical activity directed at analyzing the hygienic characteristics of the working environment [7, 8].

Here, students are systematically taught the mechanisms of physical, chemical, biological, and psychophysiological factors influencing the human body, hygienic standards, and the preventive principles of sanitary control. In this process, hygienic knowledge is utilized not merely as theoretical data, but as an analytical tool necessary for analyzing real situations in the industrial environment. The target component of the methodology is directed toward developing the student's hygienic thinking, enabling them to identify sanitary-risk factors in the workplace, evaluate their impact on health, and design preventive measures. For instance, scenarios such as assessing the risk of pneumoconiosis in a highly dusty industrial environment or determining the likelihood of thermoregulation failures in workers operating under high-temperature conditions are considered objects of problem-based analysis. Such situations serve to develop students' skills in hygienic analysis and preventive thinking [2]. At the same time, the content structure encompasses the reflexive, preventive, modeling, and technological phases of RPMT technologies: Reflexive stage: Students are engaged in understanding and analyzing hygienic problems. Preventive component: Hygienic risk factors are identified, and their impact on health is assessed. Modeling step A hygienic model of the production environment is created, and the theoretical foundations of sanitary control are formed. Technological framework: Opportunities for developing hygienic prevention measures and applying them in practical activity are analyzed. As a result, the target and content structure serves to systematically develop students' hygienic thinking, sanitary-analytical activity, and professional preventive decision-making competencies. This constitutes the methodological basis for forming students' metapreventive competence in the process of teaching occupational hygiene [3].

Technological and Organizational Integration Secondly, the harmony of technological and organizational components is an important pedagogical factor ensuring the effective implementation of the methodology. These components serve to systematically organize the educational process, integrate hygienic knowledge with practical activity, and develop students' sanitary-preventive thinking. The technological component includes the stages of reflexive analysis, preventive assessment, hygienic modeling, and the application of sanitary technologies within the RPMT framework during the educational process. The organizational component ensures the systematic implementation of these processes based on the forms of educational sessions, didactic tools, and pedagogical cooperation. Within the technological component, students' activities in analyzing hygienic situations are organized through problem-based learning tasks, modeling hygienic situations, and educational scenarios closely simulated to the production environment. For example, students analyze situations such as evaluating microclimate conditions in an industrial enterprise, analyzing the effects of dust factors on the respiratory system, or determining the compliance of workplace noise levels with hygienic norms. In this process, students acquire skills in analyzing sanitary monitoring data, assessing hygienic risks, and developing preventive measures. The organizational component includes pedagogical conditions that facilitate the effective organization of the educational process. Here, educational sessions are organized in the forms of lectures, seminars, problem-based analysis, and interactive discussions, where students actively participate in the collective analysis of hygienic situations [13]. This process serves to develop students' analytical thinking, identify sanitary determinants, and form competencies for the prognostic assessment of hygienic risks. The integration of technological and organizational components ensures a seamless connection between hygienic knowledge and practical activity in the educational process. As a result of such a pedagogical approach, students are formed as specialists ready to systematically analyze hazardous factors in the working environment, develop preventive measures for sanitary control, and make hygienic decisions aimed at creating healthy working conditions. This stands as one of the crucial methodical foundations for developing students' metapreventive competence in teaching occupational hygiene.

Assessment and Reflexive Monitoring Mechanisms Thirdly, the integration of assessment and reflexive monitoring mechanisms into the methodical system serves to determine the effectiveness of the process of developing students' metapreventive competence and to continuously improve it. In this process, assessment manifests not merely as a tool for determining the final result, but as a pedagogical mechanism aimed at tracking the dynamic development of the student's hygienic thinking, sanitary-risk analysis skills, and preventive decision-making activities. The assessment system is based on a comprehensive analysis of the level of students' assimilation of hygienic knowledge, their ability to identify sanitary determinants in the production environment, and their skills in prognostically evaluating hygienic risk factors. Diagnostic tasks, analysis of problem-based hygienic situations, practical assignments aimed at assessing sanitary risks, and analytical written works are utilized for this purpose. These assessment tools allow for determining the student's theoretical preparation alongside the level of their hygienic analysis activity and preventive thinking [4]. Reflexive monitoring is an important pedagogical process aimed at analyzing the student's educational activity, evaluating the validity of accepted hygienic decisions, and perfecting their professional thinking process [6]. During the process of analyzing hygienic situations, students discuss their conclusions, compare them with scientific foundations, and reflexively evaluate the effectiveness of sanitary-preventive decisions. The systemic application of assessment and reflexive monitoring mechanisms serves the consistent development of competencies in developing students' hygienic thinking, analyzing sanitary monitoring results, and scientifically evaluating occupational risk factors in the working environment.This is considered one of the important methodical factors in forming metapreventive competence in teaching occupational hygiene [5]. Furthermore, this methodology enhances the student's personal activity, independence, and sense of responsibility, serving to develop their analytical activity directed toward independently analyzing hygienic problems, identifying sanitary determinants in the production environment, and scientifically evaluating occupational risk factors. In such a pedagogical approach, the student appears not as a passive participant in the educational process, but as an active subject in the process of studying hygienic situations, analyzing sanitary monitoring results, and developing preventive measures. During this process, students' independent thinking, reflexive evaluation of hygienic situations, and skills in the prognostic analysis of sanitary-risk factors in the working environment develop consistently. Simultaneously, students learn to substantiate decisions related to sanitary-preventive activities, apply hygienic standards in practical situations, and develop recommendations aimed at ensuring healthy working conditions. Such activity forms professional responsibility, hygienic thinking, and preventive decision-making competencies in students, strengthening their readiness for future sanitary-preventive activity.

To statistically analyze the experimental work and evaluate the efficiency of the obtained results, a comprehensive review of relevant methodological sources was performed [15]. One of the primary approaches utilized to verify the enhancement of educational efficiency and establish the validity of empirical data involves rigorous statistical proof of reliability. In this study, to process the experimental results and validate the efficiency of the developed framework in advancing preventive medicine students' metapreventive competence through the Reflexive-Preventive Modeling Technology (RPMT), Pearson's chi-squared test (χ^2) was deployed as the primary mathematical-statistical method.

Sources indicate that applying the χ^2 method requires testing the hypothesis that the population—namely, the educational process—follows a normal distribution law. In order to compare the achievements obtained in the experimental and control groups during the experimental work, the average value of the assessment score is:

$$X = \frac{1}{n}\sum_{i=1}^{n} n_i x_i \qquad Y = \frac{1}{n}\sum_{j=1}^{n} n_j y_j$$

Where: X_i, Y_j – achievement indicators, which accept the values of high level - 5, intermediate level - 4, and low level - 3 in the research.

n_{ij} – the frequency of scores (number of repetitions);

n – the total number of students participating in the experiment.

In the research, the null hypothesis H0 assumed that the expected probabilities for the types of assessment in the experimental and control groups are equal ($p_{11}=p_{21}$, $p_{12}=p_{22}$, … $p_{1s}=p_{2s}$) while the alternative hypothesis H1 assumed that ($p_{11}\neq p_{21}$, $p_{12}\neq p_{22}$, … $p_{1s}\neq p_{2s}$) was accepted. To test this statistical hypothesis, the χ^2 criterion was utilized: Note: obs – observation(s).

$$\chi^2_{obs} = \frac{1}{n_1 n_2}\sum_{i=1}^{C}\frac{(n_1 Q_{2i} - n_2 Q_{1i})^2}{Q_{1i} + Q_{2i}}$$

Where χ^2 (Pearson's chi-squared test) is the statistical value, while n1 and n2 represent the number of students in the experimental and control groups, respectively.

Where Q_1 and Q_2 are the quantities of scores obtained relative to the types of assessment in the experimental and control groups, respectively.

As a pedagogical hypothesis, the value of χ^2 emp is compared with χ^2crit. If $\chi^2_{\mathbf{emp}} \geq \chi^2_{\mathbf{crit}}$ the null hypothesis H_0 (which assumes that the results obtained in the experimental groups are ineffective) is rejected, and the alternative hypothesis H_1 (which establishes the effectiveness of the results in the experimental groups) is accepted.

According to the essence of the method used in the research, the next stage requires finding the coefficients of variation (dispersion coefficients) for both groups. To achieve this, the sample variances must be determined.

Based on the sample variances, the standard deviations are calculated using the following formula:

$$S_x = \sqrt{\sum_{i=1}^{n} n_i (x_i - x)^2 / n - 1}$$

$$S_y = \sqrt{\sum_{i=1}^{n} n_i (y_i - y)^2 / n - 1}$$

Confidence deviations of the assessment are determined using the critical point value. Using the values representing the confidence deviations of the assessment, confidence intervals must be determined for both groups, and they are calculated using the following formulas:

$$\overline{X} - t_\gamma \cdot \frac{S_x}{\sqrt{n}} \leq a_x \leq \overline{X} + t_\gamma \cdot \frac{S_y}{\sqrt{n}}$$

$$\overline{Y} - t_\gamma \cdot \frac{S_x}{\sqrt{n}} \leq a_y \leq \overline{Y} + t_\gamma \cdot \frac{S_y}{\sqrt{n}}$$

Based on a significance level of α = 0.05, it is verified that the average score indicators belonging to the experimental groups are higher than those of the control groups, and that the resulting intervals do not overlap. Here, the normalized deviation is determined based on the confidence probability p. The degree of freedom is found using the formula K = C - 1. Since the experiment using the χ^2 criterion was conducted utilizing three types of assessment among the selected students, C = 3. Given that, if we set p = 0.05, then K = C - 1 = 2, and the critical value obtained from the χ2 table is χ2crit = 5.99.

Since C = 3 in the experiment, it is calculated based on the following formula:

$$\chi^2{}_{obs} = \frac{1}{n_1 n_2}\left(\frac{(n_1Q_{21} - n_2Q_{11})^2}{Q_{11} + Q_{21}} + \frac{(n_1Q_{22} - n_2Q_{12})^2}{Q_{12} + Q_{22}} + \frac{(n_1Q_{23} - n_2Q_{13})^2}{Q_{13} + Q_{23}}\right)$$

The baseline (pre-experimental) indicators obtained from the tests conducted to determine the academic achievement levels of the experimental and control groups in the selected educational institutions are presented in the tables (Table 1). Statistical analysis of the baseline results (mean value, effectiveness, variance, and variation indicators) for determining the level of development of metapreventive competence of students in the field of medical prevention based on RPMT technology:

Preliminary results on determining the developmental level of metapreventive competence in students of preventive medicine.

Table 1

HEIs	Criteria	Groups	Average value	Effectiveness	Variance	Coefficient of Variation
Fergana Medical Institute of Public Health	Motivational	EG	3.37		0.07	2.1%
		CG	3.38	1.00	0.07	2.2%
	Cognitive	EG	3.35		0.07	2.0%
		CG	3.35	1.00	0.07	2.1%
	Activity-based	EG	3.36		0.07	2.1%
		CG	3.36	1.00	0.07	2.2%
Andijan State Medical Institute	Motivational	EG	3.36		0.07	2.1%
		CG	3.36	1.00	0.07	2.1%
	Cognitive	EG	3.38		0.07	2.1%
		CG	3.38	1.00	0.07	2.2%
	Activity-based	EG	3.34		0.07	2.1%
		CG	3.34	1.00	0.07	2.2%

Urgench State Medical Institute	Motivational	EG	3.35		0.07	2.1%
		CG	3.36	1.00	0.07	2.1%
	Cognitive	EG	3.34		0.07	2.0%
		CG	3.34	1.00	0.07	2.1%
	Activity-based	EG	3.34		0.07	2.1%
		CG	3.35	1.00	0.07	2.1%
All educational institutions	Motivational	EG	3.36		0.04	1.2%
		CG	3.37	1.00	0.04	1.2%
	Cognitive	EG	3.35		0.04	1.2%
		CG	3.36	1.00	0.04	1.2%
	Activity-based	EG	3.34		0.04	1.2%
		CG	3.35	1.00	0.04	1.2%

A similar statistical analysis of the final results (chi-squared value, critical value, confidence intervals, and criteria conclusions) on determining the development level of metapreventive competence of students in the field of preventive medicine based on RPMT technology is presented below (Table 2).

Statistical analysis of final results on determining the developmental level of metapreventive competence in students of preventive medicine.

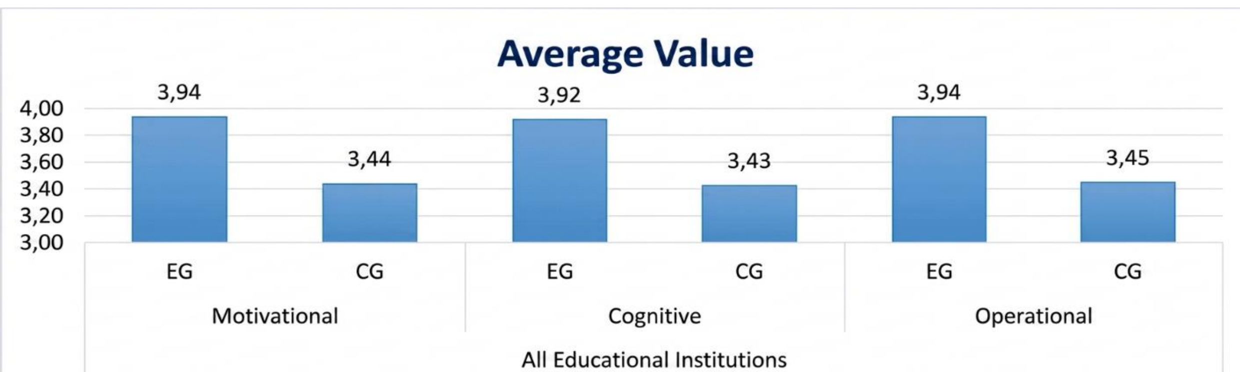
Table 2

HEIs	Criteria	Groups	Average value		Effectiveness	Variance	Coefficient of Variation
Fergana Medical Institute of Public Health	Motivational	EG	3.95			0.08	2.0%
		CG	3.44		1.15	0.08	2.3%
	Cognitive	EG	3.94			0.08	1.9%
		CG	3.42		1.15	0.08	2.2%
	Activity-based	EG	3.92			0.08	2.0%
		CG	3.43		1.14	0.08	2.2%
Andijan State Medical	Motivational	EG	3.94		1.15	0.08	1.9%

Institute		CG	3.43			0.08	2.2%
	Cognitive	EG	3.92			0.08	2.0%
		CG	3.43		1.14	0.08	2.2%
	Activity-based	EG	3.96			0.08	2.0%
		CG	3.46		1.14	0.08	2.3%
Urgench State Medical Institute	Motivational	EG	3.94			0.07	1.9%
		CG	3.44		1.14	0.08	2.2%
	Cognitive	EG	3.90			0.08	1.9%
		CG	3.43		1.14	0.08	2.2%
	Activity-based	EG	3.94			0.08	1.9%
		CG	3.45		1.14	0.08	2.2%
All educational institutions	Motivational	EG	3.94			0.04	1.1%
		CG	3.44		1.15	0.04	1.3%
	Cognitive	EG	3.92			0.04	1.1%
		CG	3.43		1.14	0.04	1.3%
	Activity-based	EG	3.94			0.04	1.1%
		CG	3.45		1.14	0.04	1.3%

According to the obtained results, the fact that the average values for the development level of metapreventive competence of students in the direction of Medical Preventive Care based on RPMT technology differ between the experimental and control groups, the existence of efficiency, the non-overlapping of the confidence intervals, and the empirical (observed) value of the Chi-square criterion being greater than the critical value lead to the acceptance of the H1 hypothesis.

Figure1.



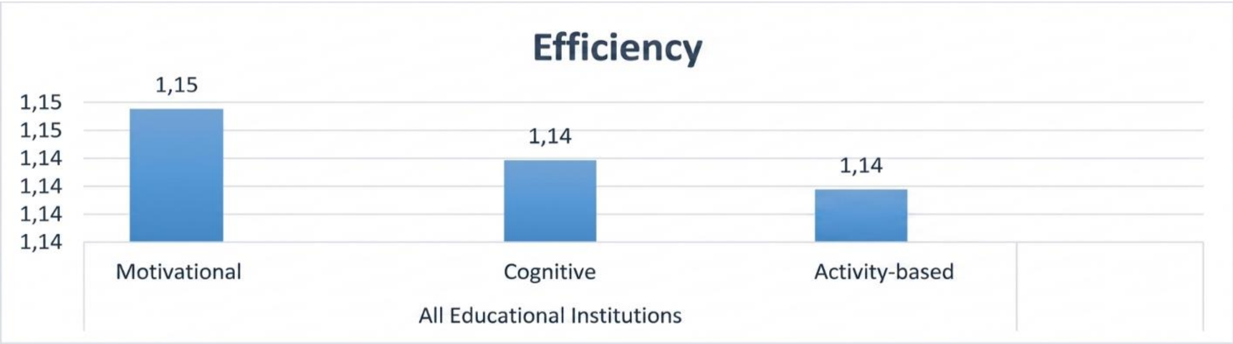
Dynamics of the average values of the final results on determining the development level of metapreventive competence of students in the field of Preventive Medicine based on RPMT technology (experimental and

control groups).

Confidence intervals of the average proficiency values of the final results on determining the development level of metapreventive competence of students in the direction of Medical Preventive Care based on RPMT technology.

Therefore, according to the statistical analysis of the final results on determining the development level of metapreventive competence of students in the direction of Medical Preventive Care based on RPMT technology, the effectiveness of the conducted research work was proven through

Figure2.



statistical methods, demonstrating that the development levels of diagnostic competence among the students in the experimental groups based on RPMT technology are significantly higher. Thus, it was determined that the development level of metapreventive competence of students in the direction of Medical Preventive Care based on RPMT technology is higher by 1.15 times (15%) according to the motivational criterion, by 1.14 times (14%) in efficiency according to the cognitive criterion, and by 1.14 times (14%) in efficiency according to the operational criterion. This indicated that the development level of hygienic metapreventive competence among the students in the experimental group is higher than that of those in the control group. Consequently, the final results obtained regarding the development level of hygienic metapreventive competence among the students in the experimental groups are highly effective.

CONCLUSION

1. The research findings demonstrated that developing the metapreventive competence of preventive medicine students is one of the key priorities of the modern medical education system. This development is fundamentally grounded in the integration of core professional components, including hygienic thinking, the identification and assessment of sanitary-hygienic risks, and effective preventive decision-making.

2. An analysis of the competency structure of metapreventive competence indicated that it comprises diagnostic, analytical, prognostic, and reflexive components. The harmonious development of these elements shapes a student's capacity to comprehensively evaluate hygienic scenarios and execute efficient preventive activities. From a pedagogical and psychological standpoint, fostering a student's independent reasoning, critical analysis, and professional motivation serves as a driving factor in this process.

3. The methodology developed within the framework of this study proposed a systemic model for fostering students' metapreventive competence based on the Reflexive-Preventive Modeling Technology (RPMT). Focused on modeling hygienic situations, detecting sanitary-hygienic risks, and engineering preventive models, this framework successfully transformed the educational process from passive theoretical knowledge acquisition into an interactive system driven by the simulation of professional activities.

4. Educational sessions organized under the RPMT framework led to a statistically significant advancement in students' hygienic thinking, analytical reasoning, and preventive decision-making skills. In particular, the deployment of simulated hygienic situations, case studies, and structured reflexive feedback loops enhanced students' professional

readiness and contributed to the systemic formation of their metapreventive competence.

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