• **Step-by-step learning.** Material is introduced gradually: from simple examples to algorithms.

• **Comparison of theory and practice.** Theoretical statements are verified on specific graphs.

• **Research skills.** Students formulate hypotheses and test them experimentally.

• **Digital environment.** Online tools make it possible to organize learning both in the classroom and in a distance format.

The use of the Graph Online service in studying the topic of graph coloring enhances the effectiveness of learning. Visualization of algorithms contributes to a better understanding of their logic, while the opportunity to experiment with different graphs develops skills of independent analysis. Moreover, the use of online services fosters the development of students' critical thinking: they learn to compare the results of different algorithms, analyze their efficiency, and draw conclusions about the applicability of particular methods.

Conclusion. The use of the Graph Online service in studying the topic of graph coloring makes the learning process more visual, interactive, and effective. The combination of theoretical material with practical tasks contributes to a better understanding of key concepts, the development of research skills, and the formation of a sustained interest in the academic discipline «Discrete Mathematics».

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METHODS FOR DETERMINING FAT CONTENT IN FEEDS WITH CONSIDERATION OF MEASUREMENT UNCERTAINTY

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Keywords. Raw fat content, GOST 32905-2014, measurement uncertainty, metrology, Soxhlet method, NIR spectroscopy, repeatability and reproducibility, Type A and Type B uncertainty.

Objective of the Research. The determination of raw fat content in animal feeds, compound feeds, and feed raw materials represents a critical aspect of quality control in agricultural production. Accurate measurement of fat content is essential for ensuring nutritional value, compliance with regulatory standards, and product safety. However, existing methodologies often lack comprehensive consideration of measurement uncertainty, which can lead to significant errors in analytical results.

This research aims to develop and validate a systematic approach for determining raw fat content in feeds while accounting for all sources of measurement uncertainty. Specifically, the study focuses on:

1. analysing and comparing established methods for raw fat content determination according to GOST 32905-2014 (ISO 6492:1999).
2. developing a mathematical framework for incorporating measurement uncertainty into fat content calculations.
3. validating the proposed methodology through comparative analysis with reference values and inter-laboratory test data.
4. implementing a computational algorithm for automated calculation of fat content with uncertainty estimation.

The integration of uncertainty analysis into the determination process is particularly significant as it aligns with international metrological standards (ISO/IEC Guide 98-3) and enhances the reliability and comparability of results across different laboratories and analytical settings [1].

Material and Methods. The study employed multiple methods for fat content determination, including the Soxhlet extraction technique (using petroleum ether with 6-hour extraction cycle and drying at 103°C), Gerber and Babcock methods for dairy products, and NIR spectroscopy as a non-destructive alternative. Measurement uncertainty was systematically evaluated according to ISO/IEC Guide 98-3, incorporating Type A uncertainty (u_A = s/√n) from repeated measurements and Type B uncertainty (u_B = Δm/√3) from equipment specifications to calculate combined (U_I) and expanded (U) uncertainties. The analytical methods were classified by approach, speed, destructiveness, and cost, with the Soxhlet method providing highest accuracy but requiring significant time investment, while NIR spectroscopy offered rapid analysis at higher equipment costs. A computational algorithm implemented in Pascal with Delphi compiler automated fat content calculations according to GOST 32905-2014, incorporating input validation, automatic uncertainty estimation, and graphical data visualization for laboratory application.

Results and Discussion. The computational algorithm for determining raw fat content in feeds was rigorously validated against reference values from GOST 32905-2014 (Tables A.1 and A.2). Validation results demonstrated exceptional accuracy, with perfect matches for critical samples including fishmeal ($w_{\text{ref}} = 78.0\text{g/kg}$, $w_2 = 78.0\text{g/kg}$) and whole milk powder ($w_{\text{ref}} = 23.4\text{g/kg}$, $w_2 = 23.4\text{g/kg}$). For all tested samples, absolute discrepancies remained well below the specified repeatability (r) and reproducibility (R) limits, confirming the algorithm's compliance with international standards.

Sensitivity analysis revealed the algorithm's differential response to input parameter variations. Using a base case ($m_4 = 5.0\text{g}$, $m_5 = 9.32\text{g}$, $m_6 = 9.52\text{g}$) where $w_2 = 40.0\text{g/kg}$, a 1% increase in sample mass ($m_4 = 5.05\text{g}$) yielded $w_2 \approx 39.6\text{g/kg}$, while a 1% decrease ($m_4 = 4.95\text{g}$) resulted in $w_2 \approx 40.4\text{g/kg}$. In contrast, equivalent variations in residue mass (m_6) produced significantly larger changes: $m_6 = 9.6152\text{g}$ (+1%) yielded $w_2 \approx 41.9\text{g/kg}$, while $m_6 = 9.4248\text{g}$ (-1%) resulted in $w_2 \approx 38.1\text{g/kg}$. This demonstrates approximately 4.8% variation in results with 1% change in m_6 versus only 1% variation with equivalent change in m_4, highlighting the critical importance of precise residue weighing.

The uncertainty framework was thoroughly validated according to ISO/IEC Guide 98-3 standards. Type A uncertainty ($u_A = 0.000576\text{g}$) was derived from repeated measurements, while Type B uncertainty ($u_B = \frac{0.001}{\sqrt{3}} \approx 0.000577\text{g}$) accounted for weighing equipment error. The combined standard uncertainty was calculated as:

$$U_I = \sqrt{0.000576^2 + 0.000577^2} \approx 0.000707\text{g},$$

with expanded uncertainty ($k = 2$):

$$U = 0.000707 \times 2 = 0.001414\text{g}$$

These calculations were verified against manual computations, showing perfect agreement and confirming the algorithm's reliability in uncertainty estimation.

A comparative analysis of analytical methods revealed significant differences in practical application. The Soxhlet method provides the highest accuracy but requires 6 hours per analysis, making it time-intensive. The Gerber method offers rapid results (approximately 1 hour) but is limited to dairy products. NIR spectroscopy provides non-destructive and rapid analysis but requires expensive equipment. The developed computational approach, when integrated with the Soxhlet method, achieves optimal precision while incorporating comprehensive uncertainty analysis [2].

Error source analysis identified the precise contributions of each parameter to total uncertainty:

- mass of the flask (m_5): 49.65%
- mass of the residue (m_6): 49.65%
- mass of the sample (m_4): 0.05%
- repeatability (w_2): 0.65%

This distribution demonstrates that m_5 and m_6 collectively contribute 99.3% to total uncertainty, while m_4 contributes only 0.05%. This critical insight indicates that improvements in balance accuracy for m_5 and m_6 measurements would significantly enhance overall analytical precision.

The integration of measurement uncertainty into fat content determination represents a significant advancement in analytical metrology for feed analysis. This approach not only enhances result reliability but also ensures compliance with international standards, ultimately contributing to improved quality control in agricultural production. Future development should focus on implementing higher-precision weighing equipment ($\Delta m \leq 0.0005\text{g}$) and expanding the algorithm to support Category B samples requiring hydrolysis, which would further enhance analytical capabilities while maintaining compliance with GOST 32905-2014 requirements.

Conclusion. The research successfully developed and validated a comprehensive approach for determining raw fat content in feeds with consideration of measurement uncertainty. Key achievements include:

1. Algorithm Development. The implemented algorithm in Pascal (Delphi) accurately calculates fat content while incorporating Type A and Type B uncertainties. The program's results matched reference values from GOST 32905-2014 with absolute discrepancies below repeatability and reproducibility limits.

2. Uncertainty Framework. The developed uncertainty calculation framework adheres to ISO/IEC Guide 98-3 standards and provides a complete assessment of measurement reliability. The analysis revealed that weighing errors for m_5 and m_6 contribute approximately 99.3% to total uncertainty, emphasizing the need for high-precision balances.

3. Method Comparison. The comparative analysis demonstrated that while the Soxhlet method provides the highest accuracy, it requires significant time investment. NIR spectroscopy offers a rapid alternative but at higher equipment costs. The choice of method should be based on the specific requirements of precision, speed, and available resources.

4. Practical Implementation. The developed software provides laboratories with a reliable tool for automated fat content determination with uncertainty estimation. The graphical interface allows operators to input data and view results with uncertainty values, simplifying data interpretation.

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