UDC 004.8 **Digital technologies: IT solutions, automation, artificial intelligence**

APPROACH TO IMAGE PREPROCESSING FOR HOUSEHOLD WASTE CLASSIFICATION IN CIRCULAR ECONOMY

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The relevance of the research is determined by the growing need for reliable digital technologies for sorting household waste in the logic of the circular economy and light industry, where the accuracy of computer vision directly affects the purity of fractions, resource conservation and recycling economics [1]. Practice shows that even modern deep learning architectures demonstrate instability in realistic scenes with variable lighting, background impurities, glare, pollution and partial overlaps of objects, as well as under conditions of class imbalance and shifts in distributions between collection sites [2, 3]. Increasing the complexity of models in itself does not eliminate these factors, since the source of degradation is heterogeneity and uneven quality of input data [4]. This leads to a transition from the traditional understanding of preprocessing as a one-time step to the interpretation of image preparation as an integrated, quality-controlled pipeline that directly participates in the formation of the training subsample, in the definition of partitioning protocols and in the procedures for stabilizing training [5].

The aim of the work is to substantiate and experimentally verify the methodology of an intelligent image preparation pipeline for stable multi-class classification of household waste in field conditions. The central idea is to shift the emphasis from exclusively architectural innovations to data quality control, which includes a systematic assessment of technical and scene-specific frame quality indicators, purposeful formation of training subsamples and the discipline of experimental reproducibility. The task was formulated in the multi-class classification mode on thirty categories of household waste items [6], where the basic recognition kernel is MobileNetV3-Small [7] with feature transfer and additional training for a specific domain [8]. This architecture was chosen considering the ratio of computational cost and sufficient expressiveness for the task, as well as taking into account future integration into production pipelines with limited resources [9].

The methodology of the image preparation pipeline is based on a multi-component assessment of the quality of input frames with subsequent controlled influence on the learning process. At the first stage, a non-reference assessment of sharpness, exposure balance, contrast and noise characteristics is performed, taking into account possible local highlights and areas of insufficient lighting, and the degree of background impurities that can mislead the model regarding class features is also determined. The obtained indicators are not considered in isolation: they are integrated into a consistent frame informativeness indicator, which is used not for rigid exclusion of a significant part of the data, but for selective control of selection thresholds and for the formation of target subsamples [10]. The key principle is to preserve the representation of rare classes and scenes, which prevents the degradation of the coverage of subject categories and minimizes the risk of excessive data “cleaning”.

The training cycle is implemented in such a way that the data quality module is

not a pre-module filter, but a full-fledged participant in the optimization. For this, a series of controlled training sessions is defined with fixed versions of libraries, configuration files, initial values of random number generators and partition protocols into training, validation and test sets. Compliance with these conditions guarantees the reproducibility of experiments and makes the interpretation of the impact of the image preparation pipeline correct. During each session, the same basic architecture and set of hyperparameters are used, and the difference lies only in the state of the quality pipeline: the "base" mode works with "raw" data with minimal normalization, the "target" mode – with the use of the described integrated quality assessment scheme and guided selection, as well as with carefully selected augmentation operations that simulate field conditions, in particular, lighting variations, moderate affine transformations and light occlusions without distortion of key class features.

Particular attention is paid to data partitioning protocols, as they determine the fairness of the comparison and the sensitivity to distribution shifts. Schemes that model inter-site differences and differences in shooting conditions are used, for which parts of the data associated with similar scenes are not allowed to be simultaneously in the training and final sets [11]. This allows us to evaluate not only the average values of the metrics, but also their behavior in subsets that reflect specific usage scenarios, in particular scenes with overexposure, poor sharpness, an increased number of small objects and the presence of backgrounds with uniform texture. To fix the stability, an approach was used in which, along with the standard indicators of accuracy, completeness and F1-measure, the variability of these metrics between partitions and in thematic subsets that reproduce critical cases for operation is considered [12]. This formulation shifts the focus to the reliability of the model's behavior, which is no less important for production lines than the increase in the average values of the indicators.

Several aspects are highlighted within the experimental part. First, the behavior of the basic configuration and the configuration with the quality pipeline enabled on identical partitions is compared, which allows us to assess the contribution of image preparation itself. Second, the sensitivity to the choice of thresholds of the integral indicator of informativeness for different classes and scenes is investigated, which makes it possible to adjust the compromise between the breadth of coverage of the training data and their purity. Third, the impact of selectively replenishing the training subsample with examples that in previous sessions led to recognition instability is considered; this creates the basis for moderate, controlled retraining without losing overall reproducibility. In all cases, the inclusion of any additional classification or localization modules in the method that would go beyond the defined architecture is avoided; The study is purposefully focused on the role of data quality and experimental discipline.

The practical aspect is the suitability of the proposed methodology for real-world sorting scenarios [13]. The full cycle from image acquisition to model integration protocols into the pipeline is considered, where the requirements for computational resources, delays, and determinism play a key role. The MobileNetV3-Small approach provides acceptable performance for inference modules with limited power consumption, which is important for placement on peripheral nodes. At the same time, the image preparation pipeline can function as an

autonomous input quality control unit within the acquisition system, regardless of the hardware configuration of the main recognition module, provided that agreed thresholds and logging protocols are observed. The paper emphasizes the importance of documenting data, screening parameters, and augmentation versions, since this is what ensures technological manageability in the process of scaling and transferring solutions between sites.

The limitations of the study are due to the nature of the problem and the generated data sets. The available corpora of household waste images contain scenes with different shooting conditions and different labeling rules, which complicates direct comparison of results with external works and requires special caution when generalizing conclusions. Additionally, it is taken into account that aggressively increasing the quality thresholds can reduce the diversity of training examples, which contradicts the goal of increasing the ability to generalize; therefore, the methodology uses an approach with dynamic thresholds and a guarantee of minimal representation of rare classes and scenes, which is regulated at the file configuration level and recorded in the accompanying experiment cards. Separately, the need for further analysis of the impact of specific types of augmentations on the stability of metrics in complex scenes with small objects and homogeneous backgrounds is noted. The developed software is shown in Fig. 1.

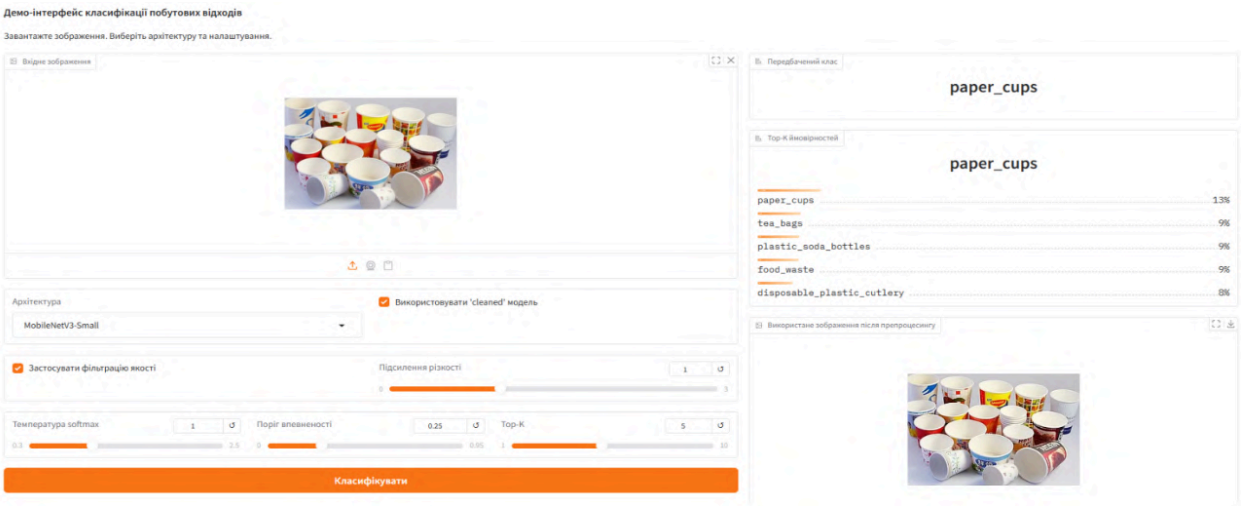

Fig. 1. Example of the developed application

The proposed methodology directly correlates with sustainable development goals through its focus on resource efficiency and reducing the negative impact of waste on the environment. The intelligent image preparation pipeline, focused on stable classification of household waste under realistic conditions, contributes to increasing the purity of fractions and reducing the loss of usable raw materials, which is in line with the logic of responsible consumption and production and supports the development of circular value chains. Increasing the reliability of automated sorting reduces the burden on landfills and incinerators, which is consistent with the reduction of greenhouse gas emissions and the ecological modernization of the urban environment.

As a result, the study forms a methodological basis for sustainable classification of household waste in the context of a circular economy by treating image preparation as an intelligent, quality-controlled conveyor integrated into the

training cycle. A coordinated scheme for multi-component quality assessment is proposed, protocols for selecting and maintaining class representativeness are described, requirements for reproducibility and discipline of configurations are given, and the principles of comparative sessions with fixing differences exclusively in the state of the quality conveyor are also defined. The set of these solutions is aimed at stabilizing the behavior of the model in variable shooting conditions and reducing the variability of metrics in subsets relevant for the real operation of sorting systems.

Prospects for further work are associated with expanding the experimental base by including additional open data sets and with the formalization of inter-site assessment protocols, which will enable comparability of results and accelerate the transfer of technologies to production. A systematic study of the impact of combinations of quality indicators and their thresholds on the stability of classification for different waste categories is planned, as well as adaptation of the methodology to defect control tasks in the light and textile industries, where the proximity of textures and the variability of shooting conditions create similar challenges for computer vision systems.

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