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TECHNOLOGICAL APPROACHES TO RUBBLE PROCESSING IN THE CONTEXT OF POST-WAR RECONSTRUCTION

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The study aimed to address the principles of circularity and sustainable development in the construction sector in the context of post-war reconstruction. General information on the classification of rubble was collected by analysing analytical reports, laws and regulatory and planning documents. The method of generalisation and systematisation was used to study the existing approaches to forming a comprehensive assessment of the efficiency of rubble processing technologies. Statistical data on the volume of destruction were processed using statistical analysis and data mining. The technical and technological analysis was used to assess the technical feasibility of sorting, crushing and further processing of construction materials. The analysis determined that as of 01.05.2024, a total of 4073 multi-apartment buildings in administrative districts in Kharkiv were destroyed. In the Saltivskyi administrative district, located in the eastern part of Kharkiv, 865 residential units were destroyed, while in the Kyivskyi district in the north-east of the city, 823 were destroyed. The study analysed the destruction in the Kharkiv region, the social and infrastructural burden in the Lviv region, and the specific environmental and transit conditions in the Zakarpattia region. The total direct economic damage caused to Ukraine since the beginning of the full-scale invasion has amounted to more than 155 billion USD. The massive destruction resulted in significant volumes of construction waste, which poses a substantial environmental threat and needs to be addressed immediately. An analysis of information from open sources and the media showed that the application of an integrated approach to the management of rubble based on the principles of the circular economy not only minimised the environmental impact of massive infrastructure destruction but also contributed to the efficient use of secondary resources in the process of restoring the affected areas. The practical significance of the study is determined by the possibility of applying the results obtained to develop effective strategies for managing construction waste in the context of post-war reconstruction, in particular through the introduction of systems for sorting, recycling and reuse of secondary materials at the national and regional levels

Keywords: *recycling; circular economy; waste; sorting; recycling; war*

INTRODUCTION

As a result of hostilities on the territory of Ukraine, many residential, commercial and industrial facilities were destroyed and damaged, which leads to a rapid increase in the volume of rubble that requires effective processing, accommodating environmental safety and the needs of the national post-war recovery. The problem of the study is the lack of an effective system for collecting, sorting and recycling construction waste generated as a result of wartime destruction, as well as the insufficient adaptation of existing technological solutions to the conditions of large-scale post-war infrastructure reconstruction in compliance with the principles of sustainable development and environmental safety.

According to the results of the study by E. Shyshkin *et al.* (2024) the integrated implementation of a system for the collection, sorting and recycling of construction waste using mobile and stationary crushing and screening plants reduced the amount of waste to be disposed of by 5-8 times, the consumption of primary mineral resources by 30-40%, and almost halved the transport costs associated with the movement of waste. Yu. Gayko *et al.* (2021) noted that the existing model of urban environment management does not ensure proper adaptation to new challenges associated with changing social, infrastructural and cultural needs of the population. This requires updating approaches to urban planning, attracting investment, and reorienting priorities towards improving the quality of life, environmental safety, and sustainable development of urban areas.

The study by Y.B. Zborivets & N.M. Klym (2025) conducted and described the development of a comprehensive roadmap for improving the financial and investment mechanism for implementing waste management projects in Ukraine, which provides for the creation of an effective multi-level system for attracting public, private and international investments aimed to modernise infrastructure, introduce innovative processing technologies and ensure sustainable development of the industry. O. Murasova *et al.* (2024) conducted research in the field of construction waste processing and utilisation. The study found that the introduction of a systematic approach to the collection, sorting and processing of construction waste, including recycling of construction waste, provides economic benefits through the reuse of materials, reduction of transportation and disposal costs, as well as the creation of new jobs in the field of environmental technologies.

In parallel, the essence of the circular economy was addressed by V. Savchenko *et al.* (2023). The study proposes a conceptual model for integrating the principles of the circular economy into the agricultural sector, incorporating the specifics of agriculture and the needs of regional development. The research has demonstrated the high potential of the circular economy in ensuring balanced nature management, increasing the efficiency of production processes and minimising the negative impact on the environment. The application of the circular economy concept in the context of reducing waste and increasing resource efficiency was studied by V. Hurochkina & M. Budzynska (2020). The study examines the possibilities of using the principles of the circular economy in various industries as a tool for achieving sustainable development and minimising environmental impact.

The problem of using construction waste and its utilisation was studied by N. Antoniuk & V. Kostiuk (2024). According to the study, an effective solution to the problem of managing construction waste accumulated as a result of armed aggression is possible only if a systematic approach is implemented, including a proper regulatory framework, the creation of infrastructure for waste sorting and recycling, and economic incentives for recycling companies. The researchers emphasise the importance of integrating circular economy principles into the processes of restoring destroyed areas, which will reduce the environmental impact, reduce waste and construction costs through the reuse of materials.

Proposals for solving the problem of disposal and recycling of construction waste generated as a result of the armed aggression against Ukraine were investigated and made by V. Kurepin (2024). The study proposed the use of innovative methods of local recycling of construction waste, incorporating the principles of the circular economy. The methodology proposed by the authors can be applied in the practice of post-war restoration of destroyed infrastructure in the de-occupied territories to reduce the anthropogenic burden on the environment and save natural resources. T. Tymochko (2022) studied the problem of the generation and management of destruction waste under conditions of occupation or active hostilities. The study proposed to supplement the regulatory framework in the field of waste management, in particular, to include in the legislation a definition and regulation of the management of destruction waste arising from military operations. To improve the current legislation, the study recommended that the Law of Ukraine No. 2320-IX "On Waste Management" (2022) should include the concept of destruction of waste generated en masse as a result of Russian armed aggression.

These studies do not sufficiently address the issues of long-term environmental monitoring of construction waste accumulation areas, assessment of their impact on soil, water resources and the air environment, as well as the integration of local communities into the processes of managing such waste in the context of post-war reconstruction. The study aimed to analyse approaches to the processing of construction debris for reuse in the context of post-war reconstruction.

MATERIALS AND METHODS

The legal basis of the study was a regulatory act and a legislative act: Resolution of the Cabinet of Ministers of Ukraine No. 1073-2022-p "On Approval of the Procedure for Management of Waste Generated in Connection with Damage (Destruction) of Buildings and Structures as a Result of Hostilities, Terrorist Acts, Sabotage or Work to Eliminate Their Consequences, and Amendments to Certain Resolutions of the Cabinet of Ministers of Ukraine" (2022), Law of Ukraine No. 2320-IX "On Waste Management" (2022). The study also analysed the national-level regulatory document Directive of the European Parliament and of the Council No. 2008/98/ЄС "On Waste and Repealing Certain Directives" (2008). The analysis of these documents was conducted to determine the legal framework for waste management in Ukraine and to harmonise national approaches with European requirements. The Resolution of the Cabinet of Ministers of Ukraine No. 1073 and the Law of Ukraine "On Waste Management" No. 2320-IX provide a regulatory framework at the state level, defining the mechanisms, principles and responsibilities of entities in the field of waste management. Directive 2008/98/EC of the European Parliament and of the Council was analysed to compare and assess the compliance of Ukrainian legislation with European standards in the context of implementing the principles of circular economy and environmentally sound waste management. The model assessment of the scale of destruction and the volume of debris was based on a report by the Kyiv School of Economics (2024).

The primary destructions in the Kharkiv, Lviv and Zakarpattia regions were selected for analysis. The rationale for this choice was based on the fact that the Kharkiv region is one of the most affected by the active hostilities in the east of the country, which led to significant damage to infrastructure, housing and the environment. The Lviv region is located in the western part of Ukraine and has experienced a predominantly sheltering role, but also significant stresses due to population displacement and infrastructure challenges.

Zakarpattia region, located in the west of the country, has unique natural and environmental conditions and is central in the transit of humanitarian aid, which causes specific destruction and pollution.

The Comprehensive restoration programme of the Kharkiv city territorial community for the period up to 2027 was analysed to assess the effectiveness of the plan for infrastructure restoration and environmental stabilisation of the region (Comprehensive restoration programme..., 2025). An analysis of the case study collection “European Practices of Environmental Responsibility and Conscious Consumption”, published under the EU Erasmus+ Jean Monnet Programme, was conducted to study examples of successful implementation of environmentally oriented initiatives that promote the implementation of circular economy principles and raise the level of environmental awareness of the population. The study analysed the following cases: the introduction of a system of separate collection and recycling of household waste in EU municipalities; the creation of reuse and repair services; educational campaigns to promote conscious consumption among the population; corporate programmes to reduce environmental pollution at enterprises; and public initiatives to reduce the use of single-use plastic.

Official data from the Kharkiv Regional Military Administration (2023), Lviv Regional Military Administration (2024) and Zakarpattia Regional Military Administration were also used. The data from the regional military administrations were collected to obtain reliable and up-to-date information on the extent of infrastructure destruction caused by hostilities, the amount of construction waste generated, and the current state of the construction waste management system. The study used a set of methods to identify and assess the volume, morphological composition, reuse potential and environmental hazard of construction debris generated as a result of the war in Ukraine. To determine the volume of waste, calculation methods were used based on the density standards of materials (concrete, brick, metal, wood, etc.), incorporating the area and degree of damage to buildings according to official data from regional military administrations. The morphological composition was determined using a chamber sampling method and subsequent manual sorting, with the mass fraction of each fraction recorded. The potential for reuse was assessed through expert analysis of the physical condition of the materials (percentage of reusable materials after cleaning or processing) and comparison with the processing technologies available in Ukraine. The level of environmental hazard was established based on an ecotoxicological assessment (determination of the content of heavy metals, asbestos and other hazardous components in the selected samples) using laboratory methods of atomic absorption spectrophotometry, X-ray fluorescence analysis and chemical testing. The method of generalisation and systematisation was used to form a comprehensive assessment of the effectiveness of technological approaches to the processing of construction debris, in particular in terms of environmental safety, economic feasibility and technical feasibility in the post-war environment. A method of analysing regulatory documents to obtain general information on the classification of construction debris and a theoretical notion of the composition of construction debris. The statistical method and data analysis for processing statistical data on damages and debris volumes for 2022-2025 were used to review existing waste generation forecasts and assess the effectiveness of processing and implemented technologies, and the method of technical and technological analysis to assess the effectiveness of equipment for sorting, grinding and processing (Kolesnichenko, 2023).

To estimate the amount of construction waste generated as a result of the destruction of residential infrastructure, a waste mass model was selected based on the standard material density indicators adopted in European approaches to construction waste management (from 2.5 to 3 t/m_3). The model addressed the type of construction (private, multi-storey), the degree of damage (partial or complete destruction), and the number of objects according to local military administrations. This model was chosen due to its versatility, ease of use and international recognition, as well as the possibility of adaptation to Ukrainian conditions in a situation of limited availability of detailed primary data. An estimate of the volume of construction waste generation was necessary to determine the scale of the problem, plan the capacity for collection, transportation and processing of debris, calculate the need for financial and technical resources, and predict the environmental impact and potential for reuse of materials. An approach based on the waste management hierarchy was considered, focusing on reuse, recycling and waste reduction. The basis for this approach was Directive of the European Parliament and of the Council No. 2008/98/EC “On Waste and Repealing Certain Directives” (2008), which set out requirements for waste management, producer responsibility and the implementation of the circular economy in EU legislation. This approach was in line with the Circular Economy model, which was based on several EU strategic documents, including reports by the European Commission: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions “Closing the loop An EU Action Plan for the Circular Economy” (2015) and Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions “A New Circular Economy Action Plan” (2020), which envisage maximum reuse of resources, minimisation of waste generation and reduction of the need for extraction of primary resources.

RESULTS

Construction and demolition debris is one of the largest sources of solid waste in the context of post-war infrastructure reconstruction. As a result of the full-scale war, tens of thousands of residential, industrial and infrastructure facilities were destroyed. This resulted in a huge accumulation of construction debris in cities and villages, which requires a systematic, scientifically based approach to their processing, sorting and reuse of the materials obtained. Such solutions are based on the principles of the circular economy and sustainable construction, namely the maximum involvement of recycled materials in the construction cycle to reduce the environmental burden, save natural resources and increase the efficiency of restoration work (European Commission, 2021).

Construction waste can be classified according to several main criteria. By origin, they are divided into demolition waste (destruction of buildings and structures), construction waste (remains of new buildings and reconstructions), and mixed waste that has not undergone initial sorting. According to their physical and chemical characteristics, the waste is divided into inert materials (concrete, bricks, stones), organic materials (wood, insulation) and hazardous materials (asbestos, paint and varnish, heavy metals). In terms of reusability, rubble is divided into materials for direct reuse (e.g., metal rebar or cleaned bricks), materials for recycling (crushed concrete, wood chips) and unusable elements, especially if they are contaminated with toxic substances (Antoniuk & Kostiuk, 2024). A separate category is construction rubble caused by hostilities. They have characteristic features: first, a significant level of contamination with fuels and lubricants, household and construction impurities; second, a potentially dangerous composition due to the possible presence of ammunition remnants; third, a large proportion of heavy reinforced concrete that requires specialised crushing. Due to these factors, care must be taken when collecting and processing construction waste of military origin, and specialists in demining and environmental monitoring must be involved. In practice, the processing of construction rubble can provide significant amounts of secondary raw materials.

An analysis of European experience in the management of construction and demolition waste has shown that, with the introduction of modern recycling technologies and proper management, EU countries have managed to achieve a recycling rate of 80-90%. The circular approach in the construction sector has a high potential that can be adapted in national practice (European Commission, 2021; Van den Berg *et al.*, 2023; Idir *et al.*, 2025). The significant potential for the reuse of construction waste has shown the feasibility of developing a recycling system in Ukraine. According to the European Demolition Association (2022), up to 60-80% of recycled crushed stone suitable for use in road construction or as a foundation can be recovered from the total volume of such waste. This has reduced the need for natural stone and reduced the environmental impact. In addition, 10-20% of construction waste consists of metals that can be melted down and reused in industry, and about 15% is wood, which is used to produce fuel pellets or chipboard. The demonstrated indicators show that the high resource potential of construction waste can be effectively realised, provided that the proper infrastructure for sorting and processing is in place. Thus, based on the results of the present observations, the study confirmed that even at the local level, there are significant amounts of waste that are not reused but are buried, which is an environmentally and economically unreasonable solution. Given the provisions of the National Waste Management Strategy until 2030, the state has set a goal of achieving a 70% recycling rate for construction and repair waste, provided that infrastructure is properly developed and quality standards are implemented (Resolution of the..., 2017). This indicates the recognition of the potential for reuse of these materials as one of the key areas of transition to a circular economy. In the context of this study, this target demonstrated the need to assess the actual state of infrastructure and the effectiveness of the standards already implemented, which determined the level of Ukraine's readiness to achieve these indicators in practice.

The analysis of national legislation and examples of similar approaches in the EU identified barriers and opportunities for adapting this experience to Ukrainian conditions. According to forecasts provided by the World Bank (n.d.), the amount of waste could increase to 2.58 billion tonnes by 2030 and 3.77 billion tonnes by 2050. In Ukraine, some landfills are 80-95% full. To address the issue, it is necessary to introduce waste recycling technologies. Based on the analysis of the collection of case studies “European Practices of Environmental Responsibility and Conscious Consumption” published under the EU Erasmus+ Jean Monnet project, it is possible to argue that the achievement of a waste recycling rate of up to 70% in Ukraine by 2030 will only be possible if large-scale infrastructure changes are implemented (Zinchenko *et al.*, 2023). It is necessary to create approximately 800 modern facilities for recycling, composting and bio-waste. At the same time, it is critical to reduce the share of household waste disposal from the current 95% to 30%. Such a scenario correlates with European waste management practices and requires not only financial investment but also effective legislative regulation and public education. Thus, the classification and theoretical notion of the composition of construction debris is critical to the development of an effective system for its recycling. This not only reduces the environmental pressure on the environment but also helps reduce the cost of reconstruction in the affected regions such as Kharkiv, Lviv and Zakarpattia by using secondary construction materials.

Statistical study of the volume of construction debris and its processing in 2022-2025

As a result of hostilities, 48,000 buildings in Ukraine's housing stock were damaged or destroyed (Kolesnichenko, 2023). The current situation in Ukraine requires not only the restoration of individual dwellings, but also the implementation of measures that will facilitate the comprehensive restoration of cities and the development of urban planning documentation at the local level. Since the beginning of 2022, the total amount of direct damage to residential and non-residential real estate, other infrastructure, vehicles and inventory is 157.2 billion USD (at replacement cost), which underscores the unprecedented scale of economic losses suffered by the country as a result of the hostilities.

According to the Kyiv School of Economics (2024), the total direct economic losses from Russia's full-scale invasion of Ukraine reached 155 billion USD. The housing sector suffered the greatest losses, as around 250,000 residential buildings were damaged or destroyed, including 222,000 private houses, over 27,000 multi-storey buildings, and 526 dormitories (Vaskiv, 2024). Damage to the sector was estimated at 58.9 billion USD. Compared to the report presented as of 30.12.2023, the analysis determined that the amount increased by 4.8 billion USD due to the transition to a different source of information for some areas. As noted, the loss of assets of enterprises and industry is at least 13.1 billion USD, and their growth continued (Approximately 10-12 million..., 2023). The study also determined that the direct losses of the agricultural sector and land resources as a result of the war amounted to 10.3 billion USD. The level of regularly growing losses in the energy sector is 9 billion USD. In total, direct losses caused by destruction and damage to public sector facilities (social institutions, educational, scientific, healthcare, cultural, sports, administrative buildings, etc.) amounted to 13.7 billion USD (Fig. 1).

Figure 1 – Consequences of the shelling of Kharkiv, May 2022

Source: O. Vaskiv (2024)

Analysis of the aforementioned data concluded that the hostilities substantially affected not only the economy, but also social stability and environmental safety. The massive destruction of residential infrastructure has led to an increased burden on the environment through the formation of new solid waste landfills, air pollution from combustion products and dust emissions during rubble removal, and contamination of soil and water sources during the destruction of communications. A final assessment of the extent of damage and destruction will be possible only after the war in Ukraine has completely ceased.

The analysis was conducted on the example of Kharkiv, Lviv and Zakarpattia regions, which were chosen due to the different nature of the military impact: direct destruction of infrastructure in the area of active hostilities (Kharkiv region), intense social and infrastructural burden due to population displacement (Lviv region) and specific environmental and transit conditions (Zakarpattia region). Since the beginning of the full-scale invasion, the territory of the Kharkiv region, including the city of Kharkiv, has been heavily damaged, which has substantially affected not only the social infrastructure but also the environmental condition of urbanised landscapes. In Kharkiv, more than 7,730 objects were damaged or destroyed, including a quarter of residential buildings, more than a hundred schools, dozens of kindergartens, hospitals, and administrative buildings (Gorodnichenko & Stepanchuk, 2024). The most damaged districts were Saltivskyi, Industrialyi and Kyivskyi. According to preliminary estimates, 70% of residential buildings and infrastructure were damaged and destroyed in the Saltivskyi district (Comprehensive restoration programme..., 2025).

As of 01.05.2024, 4,073 residential buildings in the city of Kharkiv were damaged between 2022 and 2024 as a result of armed aggression. The demonstrated indicator indicates large-scale destruction of civilian infrastructure, which has a direct impact on the socio-economic situation in the region. The massive damage to the housing stock has led to an increase in the number of internally displaced persons, a decline in the quality of life of the local population, and required significant resources to restore infrastructure and provide humanitarian assistance. Figure 2 provides statistics on the number of destroyed multi-apartment buildings in administrative districts in Kharkiv.

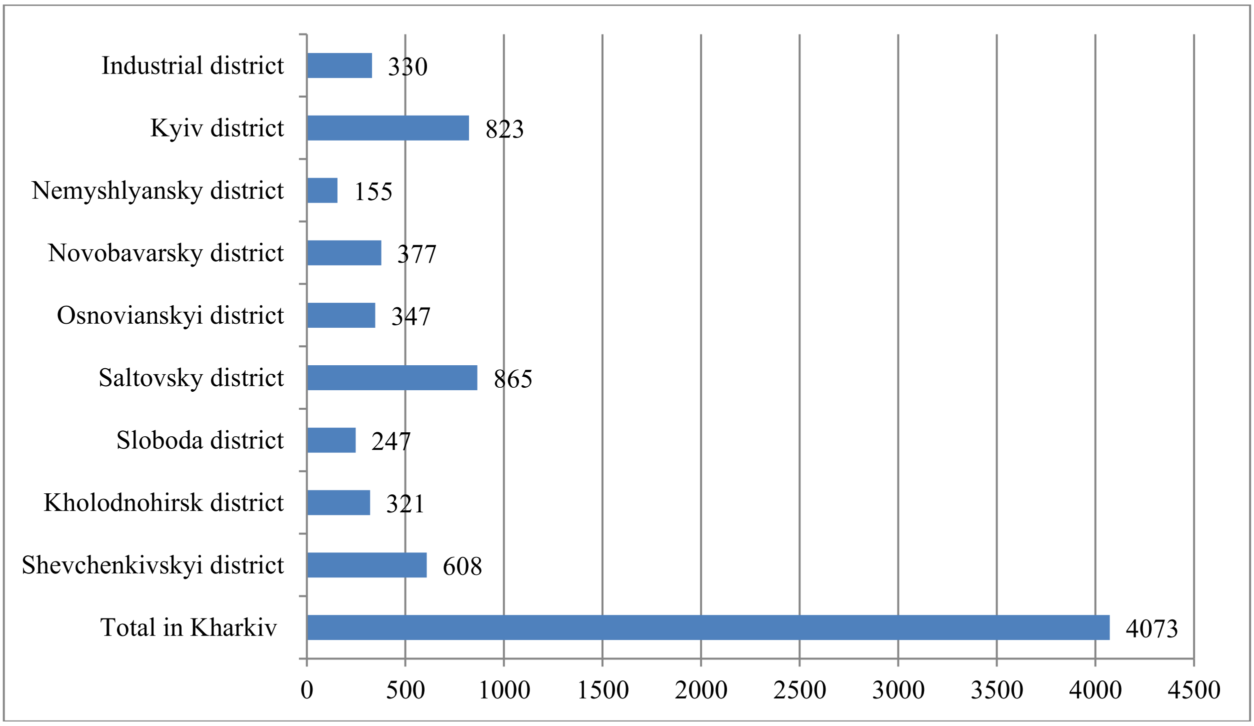

Figure 2 – Number of destroyed multi-apartment buildings in administrative districts in Kharkiv as of 01.05.2024 (units)

Source: comprehensive restoration programme for the territory of the Kharkiv city territorial community for the period up to 2027 (2025)

According to preliminary estimates, the amount of waste that may be generated during the demolition of damaged buildings will exceed 100 thousand m_3. In 2023, 12,383.05 tonnes of demolition waste were accepted at the Dergachi landfill, indicating a significant amount of construction waste, likely due to active reconstruction work or the effects of military operations. Of the total volume of this waste, 8,668.14 tonnes (about 70%) was shredded and effectively reused to strengthen temporary access roads, create an insulating layer for household waste at the landfill, and in construction (Comprehensive restoration programme..., 2025). This approach demonstrates the partial implementation of the principles of circular economy and sustainable waste management. Reusing construction waste reduces the load on the landfill, reduces the cost of new construction materials, and improves the overall environmental balance of the territory. However, it is worth addressing the residual volume of over 3,700 tonnes that remains unrecycled, which indicates that there is room for improvement in the recycling or sorting of construction waste.

Based on the data from the press service of the Kharkiv Regional Military Administration (2023), it is possible to conclude that the Kharkiv Palace of Labour, an architectural heritage site, has suffered serious structural damage: more than 3000 m^2 of roof, 70% of the roof structure, partially destroyed load-bearing walls and demolished interfloor floors. This level of damage indicates that the building cannot be simply restored and requires a full-scale reconstruction, incorporating the historical value of the property. In the cities of Izium, Kupiansk and some villages in the Kharkiv region that are under temporary occupation, there is a high level of destruction of residential and administrative infrastructure. According to official data from the Kharkiv Regional Military Administration, in 2022, the damage or destruction of buildings reached approximately 70-80% of the total building stock. Approximately 80% of residential and administrative buildings in Izyum were damaged or destroyed, which indicates the large-scale impact of hostilities on the city's infrastructure and makes it difficult to normalise the lives of the population and restore the area after liberation.

As of 1 February 2024, significant damage to the residential infrastructure was recorded in Kupiansk: 1,322 private and multi-storey buildings were included in the official register of destroyed and damaged objects. This number of damages indicates large-scale destruction caused by the hostilities and highlights the critical condition of the housing stock in the settlement, which, in turn, causes problems with housing for the local population and requires the development of a recovery strategy and priority attraction of resources for reconstruction (Zubar, 2024). According to official information from the head of the Kupiansk city military administration, as of 2024, about 40% of the community's housing stock was damaged by the hostilities, and another 10% was destroyed (Ivanova, 2024). Such large-scale destruction indicates a critical humanitarian situation in the region that requires an immediate response from government agencies and international organisations. In addition, it significantly affects the ability of the population to return to the affected areas, making it difficult to restore social infrastructure and the economic potential of the community. It is also necessary to consider that this level of destruction has put local authorities in charge of operational reconstruction planning, with a focus on the resilience and safety of the living environment in the face of threats. As a result of the large-scale destruction, there is an urgent need to dismantle the rubble and find effective ways to reuse it. The analysis of the scale of infrastructure destruction in the Kharkiv region shows a high level of physical damage caused by the hostilities. Incorporating the density of building materials and the typical composition of the debris, a preliminary model assessment of the environmental impact caused by the destruction of urban development was conducted. This suggested that the removal, disposal or temporary storage of such a volume of waste would pose a significant environmental challenge, especially given the region's limited resources and destabilised logistics.

A study of the damage in the Lviv region found that the Yavoriv military training ground suffered the greatest losses, with military infrastructure destroyed. This is an example of the direct impact of the armed conflict on anthropogenically altered territory, which necessitates an assessment of the level of environmental degradation, including soil, water and air pollution in the affected area (State Bureau of Investigation, 2022). According to the head of the Lviv Regional Military Administration (2024), 86 infrastructure facilities have been damaged since the start of Russia's full-scale invasion. Of these, 36 are private and 20 are multi-apartment residential buildings, indicating a significant impact of the hostilities on the residential sector. This level of destruction indicates not only humanitarian consequences for the population but also an increased burden on the regional infrastructure, including the environmental and social components. The damage to the industrial facility in Drohobych district has a significant impact on the regional industrial sector and has caused not only economic losses but also a threat to environmental safety due to the possible release of hazardous substances or disruption of technological processes. In the Zakarpattia region, a Russian missile damaged a gas pipeline energy facility and a railway substation in the village of Volovtsi. This event significantly affected the region's infrastructure, disrupting energy supply and transport links, which further affected the environmental situation. Thus, although the Zakarpattia region has been subject to isolated missile strikes, no significant damage has been reported, which is why the area is a substantial centre for internally displaced persons and a backup production and logistics hub.

Due to the growing strain on infrastructure and the need for rapid construction of modular housing for IDPs, there is a demand for recycled construction materials, including recycled crushed stone, wood and thermal insulation materials. There is also growing interest in the region in setting up collection and recycling centres for construction waste from the affected regions. Government support for relocated businesses has also contributed to the development of backup production and logistics capacities in the Zakarpattia region. The executive authorities and local governments have taken measures to facilitate the development of internally displaced businesses. An analysis of the relocation of enterprises demonstrated that as of January 2023, about 19% of manufacturing enterprises and 4% of construction enterprises had been relocated to the Zakarpattia region. Given this, it is possible to assume that the favourable policy of local authorities, combined with the availability of the necessary infrastructure, encourages these industries to develop in the Zakarpattia region. At the same time, the less active relocation of construction companies (4%) indicates certain barriers or specifics of their activities, which require additional analysis (Chubar *et al.*, 2023).

In the context of regional infrastructure, Olnova, a limited liability company (LLC) operating in the Lviv region and specialising in the processing of construction materials, is of particular importance. The company owns equipment for concrete crushing, crushed stone sorting, and wood restoration, which creates the basis for increasing processing capacity in the Western region. This demonstrates the company's strategic approach to developing resource-efficient production, which helps to reduce construction waste and improve environmental safety in the region. The availability of such equipment can be used by the company not only to improve the quality of secondary raw materials but also to stimulate the development of recycling infrastructure, which is a substantial step towards a circular economy. The use of the VB 750 D primary concrete crusher (Ukraine) by the Municipal Waste Management Company in the Kharkiv region demonstrates a practical approach to managing construction waste generated by demolition. Having received about 100 cubic metres of such waste, the utility company uses modern equipment that can be used for efficient processing of concrete residues, reducing the amount of waste going to landfills and promoting the reuse of materials (Vaskiv, 2024). In the Industrial district of Kharkiv, employees of the Kharkivzhytlobud utility company cleared the yard of the building No. 130 on Velyka Kiltseva Street from concrete residues (Fig. 3).

Figure 3 – The process of dismantling the rubble of house No. 130 on Velyka Kiltseva Street in the Industrial District of Kharkiv and processing concrete with the VB 750 D technological unit from Olnova LLC, May 2012

Source: O. Vaskiv (2024)

The VB 750 D technological plant (Ukraine) from Olnova LLC can be used for crushing concrete slabs into crushed stone and then sorting metal rebar with a magnet. The resulting crushed stone is used for further construction work. In 2024, one waste sorting line was put into operation in Novoyavorivsk, which was a substantial step in the development of the solid waste management system in the Lviv region. In total, there are five such lines in the region, located at solid waste landfills in the cities of Sambir, Sheptytskyi (Chervonohrad), Zolochiv, and two lines in Stryi. This indicates the active implementation of waste sorting technologies at the regional level, which contributes to the efficiency of waste management and reduces the burden on landfills (Lviv Regional Military Administration, 2024). Such infrastructure is key to the construction waste logistics system in the national recovery process. As of 2023, according to local governments, more than 450,000 tonnes of demolition waste were generated in Ukraine. This volume of waste demonstrates the significant impact of conflict events on urban and rural infrastructure and poses large-scale environmental challenges. In particular, the accumulation of such waste threatened to contaminate soil and water resources and deteriorate environmental quality in the surrounding areas. In data analysis, it is necessary to address the need to develop effective systems for the collection, disposal and recycling of construction waste to minimise the negative impact on the environment. At the same time, the lack of proper infrastructure and control mechanisms increases the risks of environmental degradation in the affected regions (Guild of

Engineers for Technical Supervision of Architectural Construction, 2024).

According to the head of the All-Ukrainian Union of Construction Materials Manufacturers, as of the end of 2024, Ukraine has accumulated approximately 100 million cubic metres of construction waste, which is equivalent to about 250-300 million tonnes of waste, given the average density of construction waste is 2.5-3 t/m^3 (Ukraine has 100..., 2024). This amount of waste was generated due to the destruction of buildings and structures, as well as active reconstruction and restoration of infrastructure after the war. Such a huge amount of waste creates a serious burden on the environment, including soil, air and groundwater pollution. At the same time, there is an urgent need to recycle at least 50-100 million tonnes of this waste as part of the national post-war reconstruction programme. To ensure the environmentally safe processing of such volumes, a system of regional sorting and processing centres should be established to handle at least 5-10 million tonnes per year.

In this context, identification of the geography of the destruction and locating potential recycling centres (particularly in Kharkiv, Lviv and Zakarpattia oblasts) has become a strategic task to ensure an uninterrupted supply of recyclable materials during the reconstruction process. Thus, the historical and geographical context has demonstrated the need for an integrated approach to the management, sorting, transportation and recycling of construction debris. This involves the creation of logistics hubs, mobile shredding stations, and the development of regional enterprises capable of adapting to the conditions of large-scale reconstruction, incorporating the specifics of the destruction in each region.

Overview of technological approaches to recycling construction rubble

Research has shown that in 2024, less than 10% of waste was recycled in Ukraine, while on an industrial scale, it was possible to recycle 80-85%, due to the unprofitability of waste reuse and recycling processes (Approximately 10-12 million..., 2023). Subsidies for the recycling of construction waste from the war were set at 90%. One of the biggest problems was waste from the destruction of infrastructure and residential buildings. A substantial technological process was waste disposal and the transition to circular use (Artemov *et al.*, 2023; Horbal & Slipachyk, 2024). Among the modern approaches that are already being implemented or have high potential for application in Ukraine, it is worth highlighting mobile crushers, which provide effective crushing of concrete and brick debris without the need to transport large volumes of materials to stationary facilities. Installations such as the VB 750 D (Ukraine) are already demonstrating their effectiveness in the Kharkiv region, quickly converting construction waste into a reusable crushed stone mixture. Another promising area is magnetic sorting, which separating metal components (reinforcement, wires) for further smelting or sale as secondary raw materials. This stage not only reduces the total volume of waste but also contributes to the return of valuable materials to the industrial cycle. The use of recycled construction materials in road construction, for example, as a roadbed base or as a filler for asphalt concrete mixtures, is also being actively researched and implemented. Within the framework of approaches to sustainable construction waste management in Ukraine, the innovative project Safe, Sustainable and Swift Reconstruction of Ukraine (n.d.), implemented with the participation of British, Dutch and Ukrainian universities and companies, deserves attention. As part of this project, mobile advanced dry recovery units are being tested to extract sand, gravel and cement from construction debris for further use in the production of new concrete. A pilot scale-up of the technology is already being implemented in certain regions, in particular in the Kharkiv, Lviv (Yavoriv) and Zakarpattia regions (Pragmatika.Media, 2024).

To overcome the consequences of the accumulation of large amounts of construction waste, it is necessary to introduce tax incentives for recycling companies and provide grants and technical assistance for the creation of recycling infrastructure (including from international partners). It would also be advisable to introduce the model of eco-industrial parks in all regions of the country, which was introduced by D. Lazarenko *et al.* (2024) and V. Bioko & L. Bioko (2023). This model will simplify the relocation of industrial enterprises in times of war and accelerate economic recovery after its end. Implementation of the eco-industrial parks model in all regions of the country will help concentrate enterprises with closed production cycles, where waste from one production becomes raw material for another; create new jobs in the field of recycling and environmental technologies; increase resource efficiency and reduce the amount of waste going to landfill; facilitate the relocation of enterprises from active hostilities, which will ensure faster production resumption, maintain economic activity and attract investment.

The cost of primary construction materials in Ukraine is much cheaper than the cost of secondary materials, due to low royalty rates for mining. It is necessary to reform the pricing of natural resources and ensure the competitiveness of recycled materials on the Ukrainian trade market. At the first stage of recycling, primary sorting of construction waste should be carried out. This is usually conducted directly at the site of destruction using front-end loaders, crawler excavators and mobile sorting plants. The materials are divided into mineral (concrete, brick, plaster, gypsum), metal (rebar, steel structures), wood, mixed and non-recyclable (e.g. asbestos). In some cases, manual sorting is used, especially to separate hazardous materials such as unexploded ordnance.

After the initial sorting, the types of materials that can be reused (such as glass, metal, plastic, and concrete) and those that cannot be recycled and must be disposed of (such as thermally deformed facade insulation elements) should be identified. Inorganic waste (concrete, bricks) can be sent to crushing plants, where it is crushed into fractions suitable for reuse. The types of crushers used are jaw (for large-sized concrete), impact (to obtain a homogeneous fraction), and cone (for mineral rocks). Magnetic separators can effectively separate scrap metal from the concrete mass, which will be subsequently transferred for melting.

The experience of European countries has shown that integrating circular economy principles into the construction waste management system not only reduces the burden on landfills but also creates added value through the reuse of resources. Austria has the highest level of construction waste recycling in Europe. A distinctive feature of the Austrian system is that construction waste is collected at the demolition site using special containers. The secondary use rate of household waste in Austria is around 60% (Advantage Austria, n.d.). In the Netherlands, a ban on the landfilling of reusable waste has been in effect since 1997, contributing to an increase in the recycling rate of construction and demolition waste to almost 100% (Van den Berg *et al.*, 2023). However, Ukraine has a problem with waste management, as well as a large number of uncontrolled landfills where not all waste is recycled. To resolve this situation in the field of waste disposal, it is necessary to amend the National Waste Management Strategy in Ukraine until 2030 to consider the specific features of the classification, distribution, use and disposal of war waste (Potip, 2023).

At the national level, the pricing system for natural resources needs to be reformed (in particular, rent rates for mineral extraction should be increased) to make recycled materials economically competitive on the domestic market. At the regional level, mobile processing technologies should be developed, especially in regions affected by hostilities, where waste transportation is difficult and costly. Construction timber, provided it is not severely damaged by mould or fire, can be processed into chipboard, fuel pellets or firewood for thermal power plants. It is advisable to consider the regulatory requirements in force in EU countries regarding the quality of biofuels. In particular, the EN ISO series of standards (in particular EN ISO 17225 “Solid biomass fuel”) and the ENplus and DINplus certification systems for pellets regulate strict criteria for the purity, safety and quality of raw materials. These standards require the absence of toxic contaminants, in particular paints, varnishes and impregnating agents containing heavy metals; the classification of wood according to the degree of contamination (clean, moderately contaminated, hazardous); as well as requirements for moisture content, ash content and calorific value for pellets and briquettes, with mandatory quality control of biofuel.

Similar principles should be introduced in Ukraine, including a certification system for recycled wood that confirms its safety for incineration or secondary use, and the burning of contaminated or hazardous wood (including chemical-treated wood) in facilities that do not have appropriate filtration systems should be prohibited. National technical regulations on the processing of construction wood into biofuels should be developed.

In Ukraine, it is technically feasible to use crushed concrete, brick and glass in cold recycling for the construction of road bases, as research has shown that asbestos cement slate, glass, brick and concrete are 5-20% more effective than traditional materials (Bidos *et al.*, 2025). After cleaning and crushing, concrete and brick fragments are used in road construction (roadbed base, asphalt cushion), the construction of foundations for temporary buildings, and the manufacture of low-quality concrete (in compliance with proportions and technical standards). The next stage after sorting is to reduce the volume of glass, metal, plastic, concrete and thermally deformed facade insulation elements. For this purpose, the city of Kharkiv used a VB 750 D crushing plant from Olnova LLC. According to technical specifications and expert reviews, this complex can reduce the volume of waste by approximately 5-8 times, depending on the type of material and its structure.

Therefore, it is recommended that Ukrainian enterprises implement the principles of circularity and recycling of sorted waste to turn it into raw materials. This will reduce the amount of waste in landfills, conserve natural resources and reduce environmental impact. After the implementation of the proposed approaches, the following options for the use of demolition waste in Ukraine will emerge: the use of recycled inert materials for road construction, the manufacture of building blocks and slabs, the use of crushed concrete as an aggregate in new concrete mixtures, the creation of noise barriers, and the formation of landscapes on reclaimed territories.

Discussion

The findings of the study confirmed that the destruction of infrastructure as a result of armed aggression against Ukraine led to an unprecedented increase in the volume of construction debris, which in turn created a complex environmental, social and economic problem that required the introduction of institutional mechanisms for the management of construction and repair waste in the context of reconstruction.

The present study found that in Ukraine, recycled building materials, in particular concrete and brick fragments, are already being used in road construction. This issue was highlighted by X. Yu *et al.* (2025), demonstrating the poorer rheological properties of asphalt after multiple recycling: the high-temperature characteristics of multiple recycled asphalt mix improved, while the low-temperature characteristics deteriorated significantly. Their results are consistent with the findings of the current study, which also confirmed that the repeated use of recycled components can increase the stiffness of road material, which has a positive effect on its thermal stability at high temperatures, but at the same time creates risks for operational reliability at low temperatures.

The reduction of waste during the reconstruction of war-damaged facilities in Ukraine required a comprehensive approach, including the recycling of construction waste, the implementation of circular economy principles, and the use of new technologies. D. Atstāja *et al.* (2022) studied this topic. The results of the study showed that for the effective reconstruction of destroyed infrastructure, it is necessary to implement approaches focused on the circular economy, in particular by using materials from destroyed buildings in cold recycling technologies for road bases, as well as creating mobile complexes for waste processing. The results of the presented study are similar to those of D. Atstāja *et al.*, as both approaches focus on the need for a comprehensive solution to the problem of construction waste disposal, the application of circular economy principles, and the implementation of modern processing technologies.

Reduction of the amount of plastic waste in Ukraine generated by the destruction of building structures is possible through the introduction of technologies for sorting, recycling and reusing plastic structural elements in accordance with the principles of the circular economy. This topic was studied by S. Ramesh & H. Patel (2025). According to the study, one of the promising solutions for plastic recycling was cyclic chemical recycling, which involved the return of polymers to their original monomers with subsequent repolymerisation into virgin plastic without loss of quality. The present study preferred the integration of mechanical sorting with the subsequent classification of plastics by type for further recycling or reuse in construction, which reduces the burden on landfills and contributes to the formation of closed resource flows. Compared to cyclic chemical processing, mechanical sorting involves lower energy consumption but limits the ability to fully restore the material's original properties.

In Ukraine, it was necessary to conduct additional research into methods for processing construction waste from demolition at the regional level. A similar problem was studied by S.A. Karanafti *et al.* (2022). The results of this scientific study show that effective management of construction and demolition waste was substantial in view of the goal of achieving a climate-neutral economy by 2050. The traditional practice of landfilling such waste is considered obsolete due to its significant negative impact on the environment. In this regard, Europe is tightening national standards and regulations for the proper management of construction and demolition waste. Similar conclusions were reached in the presented study, as the results show that the implementation of modern approaches to construction waste management, in particular sorting, reuse and recycling, can significantly reduce the environmental impact of the construction industry. In addition, it is necessary to address regional characteristics and adapt technological solutions to local conditions, which ensures increased recycling efficiency and reduced landfill volumes.

The study determined that concrete recycling in Ukraine mitigated massive landfilling of construction waste, which helped to reduce the negative impact on the environment and rational use of resources. A similar issue was raised by V. Troian *et al.* (2022). The study determined that the success of the implementation of concrete recycling technologies depended on the quality of sorting, the level of purification and technological parameters of processing, which affect the mechanical characteristics of the resulting material. In addition, the researchers noted the need to adapt regulatory requirements and standards to ensure the safety and durability of structures using recycled concrete aggregates, especially in the context of the reconstruction of war-affected areas. Similar conclusions were drawn in the study, as it was found that the technically sound use of recycled concrete also reduced the environmental burden and provided a permanent resource base for reconstruction, which is especially relevant for regions with a large amount of destroyed infrastructure.

The use of recycled concrete aggregates in Ukraine has reduced construction waste, the need for the extraction of natural non-metallic materials, and the burden on landfills, and provided a more economically and environmentally sustainable approach to infrastructure reconstruction. This topic was studied by M. Ulucan & K.E. Alyamac (2022). The study determined that concretes made using 100 % recycled concrete aggregate, subject to proper selection of the mixture composition and water-cement ratio, demonstrate satisfactory mechanical properties and less negative environmental impact compared to concretes based on natural aggregates, in particular in terms of primary energy consumption, greenhouse gas emissions and waste generation. Thus, the comparison of the results of this work with the results of the research by M. Ulucan & K.E. Alyamac confirmed that the use of recycled concrete aggregates is feasible from both a technical and environmental point of view, and, with the right technological approach, can provide an effective alternative to natural materials in the process of infrastructure reconstruction, especially in regions that have suffered large-scale destruction. It also highlighted the importance of integrating such solutions into national construction waste management and recovery strategies.

According to the conclusions of the present study, it is known that the introduction of facilities for processing construction and demolition waste in Ukraine achieved high efficiency in reducing waste disposal volumes, the burden on the environment, and contributing to the conservation of natural resources through the reuse of construction materials. I.B. Cariman *et al.* (2023) also studied this issue. The study assessed the economic feasibility of investing in construction and demolition waste processing plants, identified critical costs associated with logistics, maintenance, and waste management, and developed practical recommendations for improving the efficiency of processing and minimising financial risks. The research confirmed that the most significant barriers to the implementation of construction and demolition waste processing facilities are the high cost of transporting materials, the instability of input volumes, and the lack of incentives at the state level, which makes it difficult to achieve economic viability of projects without adequate financial support.

The study noted that in Ukraine, more than 100 million tonnes of construction waste from wood, plasterboard, asphalt shingles, bricks and clay tiles were sent to landfills, which indicated an insufficient level of recycling and the need to introduce an effective system for sorting and reusing these materials. The same problem was studied by G. Can *et al.* (2023). The researchers found that brick, as one of the most used building materials, had a high potential for reuse or recycling. This study proved that effective management of construction and demolition waste, including bricks, can significantly reduce the negative impact on the environment, reduce the need for natural resources, reduce the amount of waste going to landfills, and contribute to the implementation of a circular economy through the reuse and recycling of materials throughout their life cycle.

The study demonstrated that the generation of more than 450,000 tonnes of construction waste poses substantial environmental challenges, while the partial reuse of materials demonstrates the practical implementation of circular economy principles. R. Mack *et al.* (2024) addressed this issue. The study analysed 28 samples of ENplus A1 certified pellets, whose indicators (ash content, moisture content, K, Ca, Mg content) were compared with the requirements of the EN ISO 17225-2 standard. The study also identified the main factors affecting the level of emissions during combustion and the general quality characteristics of solid biofuel. The study by R. Mack *et al.* is devoted to the assessment of solid biofuel (ENplus A1) indicators and used laboratory analysis of the chemical and physical characteristics of materials to assess quality and emissions. In contrast, this study focused on field and regional analysis of damage to residential and social infrastructure, assessment of construction waste volumes and their impact on the environment. The similarity lay in the use of standardised approaches to resource assessment: R. Mack *et al.* applied EN ISO 17225-2 for pellets, while the methodology of the current study was based on official statistics, building material density standards and waste volume estimates to assess the environmental impact.

The massive destruction of residential and administrative infrastructure in the Kharkiv, Lviv, and Zakarpattia regions increased the volume of solid waste, polluted soil and water resources, and negatively affected the socio-economic stability of the population. Similar scientific work was conducted by G. Toscano *et al.* (2023). As part of the analysis of European approaches to biomass classification, the study assessed ash content and classified raw materials A1, A2 and B in accordance with the requirements of ISO 17225. The study considered various types of raw materials, including wood waste, sawdust and other wood processing by-products, which determined their compliance with established quality indicators. The methodology of the current study and the results are similar to the approach of G. Toscano *et al.* in terms of assessing and classifying waste for reuse and reducing its negative impact on the environment but differed in the type of raw materials and the context of application: practical restoration after destruction versus industrial analysis of wood waste.

The analysis of the results of the reviewed studies showed that recycling of construction and demolition waste was a substantial sustainable development in the context of post-war reconstruction. It was confirmed that the use of recycled materials (concrete, bricks, wood, etc.) not only reduced the environmental burden, but also saved significant amounts of natural resources, reduced the need for new materials and contributed to the formation of a closed production cycle in the construction sector.

CONCLUSIONS

– The study showed massive damage to housing stock and infrastructure as a result of hostilities in Ukraine in 2022-2025. In the Kharkiv region that was under temporary occupation, in particular in Kupiansk and Izium districts, the scale of infrastructure damage reached 70-80%, which requires urgent strategic decisions. In total, more than 48,000 residential buildings have been damaged or destroyed, resulting in the generation of about 250-300 million tonnes of construction waste. In the city of Kupiansk, where about 50% of the housing stock was destroyed, the volume of rubble reaches more than 500,000 tonnes. In 2023, more than 12,000 tonnes of rubble were disposed of at the Dergachiv landfill in the Kharkiv region, of which 70% was reused. In the western regions, in particular in Lviv and the Zakarpattia region, infrastructure damage was less severe, but energy and logistics facilities were hit, affecting the stability and security of the regions.
– The existence and development of construction waste processing enterprises and modern equipment for crushing and sorting materials are key factors in improving the environmental safety and economic efficiency of restoring affected areas. The study found that the following were technologically effective at the national and regional levels mobile crushers (in particular, the Ukrainian-made VB 750 D) for crushing concrete; magnetic sorting for the removal of metal reinforcement; the use of crushed materials in road construction and for the reclamation of landfills; sorting lines in the Lviv region, with at least five lines operating at solid waste landfills. However, the introduction of sorting line technology covers less than 10% of construction waste, which indicates the need to develop a recycling infrastructure. To recycle construction waste in Ukraine, it is recommended to expand the network of mobile crushing plants for the rapid processing of debris in areas of intense destruction; integrate circular economy principles into state and local reconstruction programmes; ensure state subsidies for recycling at a level of at least 90% of the costs of technological operations; improve accounting and monitoring of construction waste, in particular through the introduction of digital platforms for recording the volume and location of debris.
– Thus, the study highlighted the need to implement an integrated environmental, social and economic approach to the restoration of destroyed infrastructure, active implementation of circular economy principles, improvement of the construction waste management system, as well as strengthening coordination between state, local and private structures. The prospect of further research is to develop effective mechanisms for managing construction waste in the context of post-war reconstruction, including the introduction of innovative technologies for sorting, recycling and reusing materials, as well as the creation of a single open database on the scale of destruction, waste volumes and actions of responsible authorities.

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ТЕХНОЛОГІЧНІ ПІДХОДИ ДО ПЕРЕРОБКИ БУДІВЕЛЬНИХ ЗАВАЛІВ У КОНТЕКСТІ ПІСЛЯВОЄННОГО ВІДНОВЛЕННЯ

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Метою роботи було проведення розгляду принципів циркулярності й сталого розвитку у будівельній сфері в умовах післявоєнного відновлення. Збір загальної інформації щодо класифікації будівельних завалів проводився шляхом аналізу аналітичних звітів, законів та нормативно-планових документів. Для вивчення наявних підходів до формування комплексної оцінки ефективності технологій переробки завалів застосовувався метод узагальнення та систематизації. Обробка статистичних даних про обсяги руйнувань виконувалася за допомогою статистичного аналізу та аналізу даних. Техніко-технологічний аналіз використовувався для оцінювання технічної реалізованості *процесів сортування, подрібнення та подальшої переробки будівельних матеріалів. Виявлено, що станом на 01.05.2024 у місті Харкові загалом зруйновано 4073 об'єкти багатоквартирної забудови в адміністративних районах. У Салтівському адміністративному районі, розташованому в східній частині міста Харкова, зруйновано 865 одиниць житлової забудови, тоді як у Київському районі на північному сході міста – 823. У роботі були проаналізовані руйнування в Харківській області, соціально-інфраструктурні навантаження у Львівській та специфічні екологічні й транзитні умови Закарпатської областей. Сукупний показник прямих економічних збитків, завданих Україні з початку повномасштабного вторгнення, склав понад 155 мільярдів доларів. Внаслідок масових руйнувань утворилися значні обсяги будівельних відходів, які становлять серйозну екологічну загрозу та потребують невідкладного вирішення. Аналіз інформації з відкритих джерел та засобів масової інформації продемонстрував, що застосування комплексного підходу до управління будівельними завалами на основі принципів циркулярної економіки дозволяло не лише мінімізувати екологічні наслідки масового руйнування інфраструктури, а й сприяло ефективному використанню вторинних ресурсів у процесі відновлення постраждалих територій. Практичне значення дослідження полягало у можливості застосування отриманих результатів для розробки ефективних стратегій управління будівельними відходами в умовах післявоєнного відновлення, зокрема шляхом впровадження систем сортування, переробки та повторного використання вторинних матеріалів на національному та регіональному рівнях.*

Ключові слова: рециклінг; циркулярна економіка; відходи; сортування; утилізація; війна

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