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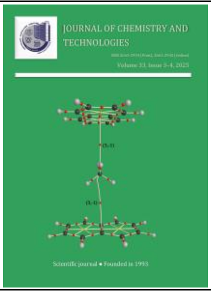

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THE IMPACT OF CHINA'S BAN ON PLASTIC WASTE EXPORTING COUNTRIES

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Abstract

Current transformations in the global trade in plastic waste are being driven by new environmental regulations, sustainability policies, and individual countries' decisions on the import of recyclables. The People's Republic of China's 2018 ban on plastic waste imports has significantly changed the structure of global recycling flows, calling into question the sustainability of the centralized recycling model. The study aims to assess the consequences of this decision for exporting countries, analyze their adaptation trajectories, and classify changes in trade dynamics in 2008–2024. The paper uses quantitative methods to analyze statistical data, builds the author's own trade flow change rate (TFCR), and applies cluster analysis using the K-means method to typologize countries by the nature of changes in the structure of plastic waste exports. Based on the data of international organizations (OECD, UNEP, ITC), regional disparities in the production and processing of plastics are characterized. Three groups of countries with different adaptation models are identified: resilient, partially adapted, and those that have lost market share. It was found that countries with a lower initial level of dependence on China were more likely to reorient to alternative markets or increase domestic capacity. Particular attention is paid to the evolution of China's environmental policy, which, after the ban, is aimed at developing its own processing technologies, controlling unauthorized imports and relocating export-oriented enterprises to Southeast Asia. It is substantiated that the current structure of the global recycling market is becoming more fragmented, asymmetric and technologically differentiated. The results of the study can be used to formulate a waste management policy, taking into account the risks inherent in new forms of environmental logistics.

Keywords: polymer feedstock; recycling system; waste trade; export dependency; cluster analysis; environmental policy.

ВПЛИВ КИТАЙСЬКОГО БАНУ НА КРАЇНИ-ЕКСПОРТЕРИ ПЛАСТИКОВИХ ВІДХОДІВ

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Анотація

Сучасні трансформації у глобальній торгівлі пластиковими відходами відбуваються під впливом нових екологічних регуляторів, політики сталого розвитку та рішень окремих держав щодо імпорту вторинної сировини. Запроваджена в 2018 р Китайською Народною Республікою заборона на імпорт пластикових відходів суттєво змінила структуру світових потоків утилізації, поставивши під сумнів стабільність централізованої моделі переробки. Дослідження спрямоване на оцінку наслідків цього рішення для країн-експортерів, аналіз їх адаптаційних траєкторій та класифікацію змін у торгівельній динаміці у 2008–2024 рр. У роботі використані кількісні методи аналізу статистичних даних, побудований авторський показник зміни торговельного потоку (TFCR), а також застосовано кластерний аналіз методом K-середніх для типологізації країн за характером змін у структурі експорту пластикових відходів. На основі даних міжнародних організацій (OECD, UNEP, ITC) охарактеризовані регіональні диспропорції у виробництві та переробці пластиків. Виявлено три групи країн з різними адаптаційними моделями: стійкі, частково адаптовані та ті, що втратили частку ринку. Встановлено, що держави з нижчим початковим рівнем залежності від Китаю швидше переорієнтувались на альтернативні ринки або наростили внутрішні потужності. Особливу увагу приділено еволюції екологічної політики КНР, яка після заборони спрямована на розвиток власних технологій переробки, контроль несанкціонованого імпорту та перенесення експортно-орієнтованих підприємств до країн Південно-Східної Азії. Обґрунтована гіпотеза щодо нинішній структури глобального ринку утилізації: вона стає більш фрагментованою, асиметричною та технологічно диференційованою. Результати дослідження можуть бути використані для формування політики управління потоками відходів, з урахуванням ризиків, притаманних новим формам екологічної логістики.

Ключові слова: полімерна сировина; система переробки; торгівля відходами; експортна залежність; кластерний аналіз; екологічна політика.

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Introduction

Plastic waste has become one of the most dangerous challenges to global environmental stability [12]; [43]. Its long decomposition period, chemical inertness and ability to microfragment make it impossible for polymers to quickly return to the natural cycle. Over the past decades, they have become a persistent source of pollution of land, oceans and food chains [42]; [53]. The problem of plastic waste has gradually gone beyond the scope of household waste disposal and has become systemic at the level of international trade, cross-border control and sustainable development. Of particular concern is the fact that even compared to other hazardous categories of chemicals – pesticides, pharmaceutical residues, organic solvents – plastic polymers demonstrate exceptionally high biopersistence, global prevalence and long-lasting ecotoxicological effects. For example, China's ban on plastic waste imports in 2018 significantly improved air quality in Chinese cities [54]. To better understand the scale of the problem, Table 1 presents a comparative assessment of typical chemical wastes based on five parameters: source, risks, duration of exposure and global prevalence.

Table 1

Comparative table of the negative impact of different types of chemical waste [2]; [9]; [13]; [14]; [21];[37] [52]; [58]; [61]

Type of chemical waste	Main sources	Main environmental risks	Duration of exposure (years)	Global prevalence
Plastic polymers (PET, HDPE, PVC)	Household packaging, textiles, construction	Microplastics, bioaccumulation, environmental pollution	100–500	Extremely high
Pesticides and agrochemicals	Agriculture	Soil poisoning, biodiversity loss	10–30	High
Pharmaceutical residues	Hospitals, pharmaceutical production	Hormonal disruption in living organisms	5–15	Medium
Solvents (organic)	Chemical industry, paint shops	Air, soil, water pollution; carcinogenicity	5–20	High
Industrial acids and bases	Metallurgy, electroplating, chemical production	Corrosion, chemical burns, soil degradation	1–10	Medium
Organochlorine compounds (PCBs, dioxins)	Chemical industry 1960–80s, transformers	Persistent pollution, DNA damage, cancer	50–100+	Low
Heavy metals (mercury, cadmium, lead)	Electronics, batteries, mining industry	Food chain accumulation, neurotoxicity	50–200	High
Radioactive waste	Nuclear energy, military facilities	Lethal radiation, mutations, long-term effects	1000+	Low

PET, HDPE and PVC constitute a separate group among plastic polymers and are the most common in consumer packaging, textiles, construction and infrastructure. These types of polymers form the basis of both household and industrial plastics, which, after the end of their life cycle, end up in domestic collection channels or international recycling. The varying complexity of their secondary processing and uneven recycling costs necessitate a more detailed classification and a responsible approach to sorting at the source of generation [16].

The problem is compounded by the rapid growth in the volume of plastic waste generated. According to OECD estimates, the annual volume exceeded 400 million tonnes, with less than 10 % of this mass entering effective recycling systems [41]. The main sources of generation are short-term consumption industries, especially in countries with high incomes or a growing middle class. Figure 1 visualises the growth dynamics of plastic waste generation, which clearly demonstrates the gap between the volume of generation and recycling.

In many countries, recycling systems were structurally unprepared to process such volumes. This led to the spread of the model of exporting plastic waste to third countries, which in some cases led to phenomena of 'ecological colonialism' [49]. However, in 2018, China, which until then had been the world's leading importer of plastic waste, decided to completely ban the import of mixed plastic waste. The so-called 'Chinese ban' [60] was a turning point in the global plastic management system and demonstrated the vulnerability of centralised recycling schemes [32]; [59]. This decision had a multifaceted effect. First, it led to an immediate reduction in imports of more than 30% and a sharp decline in exports from the US, EU, and Japan [7]. Second, it served as a catalyst for reforming national waste management systems, both through technological modernization and institutional rethinking of responsibilities [45][19]; [35].

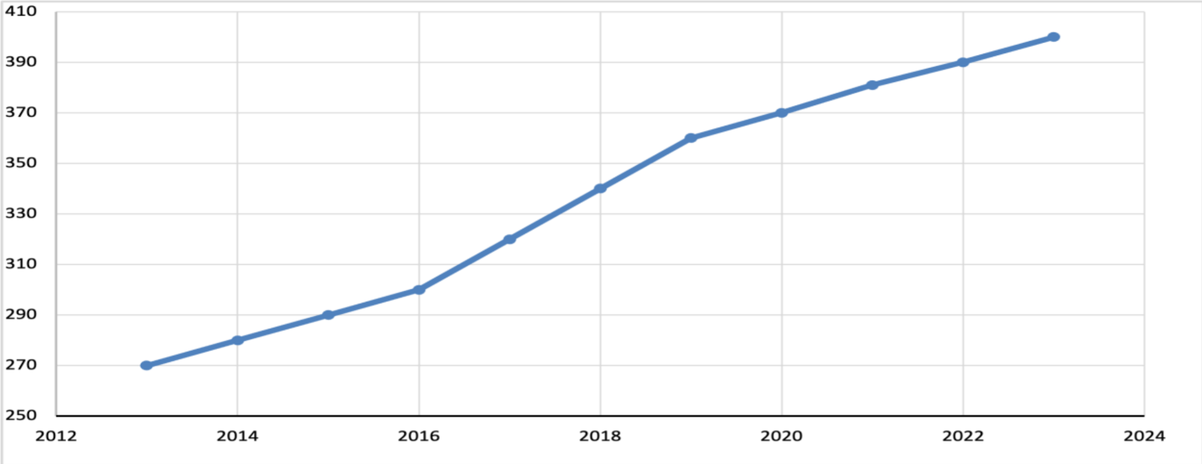

Fig. 1. Global generation of plastic waste (OECD, 2018; OECD, 2022, UNEP, 2023)

Against the backdrop of such changes, the issues of sustainability and competitive response to external challenges are taking on new significance, not only in environmental terms but also in strategic management terms [39]. In post-crisis recovery models [4] and competitive entrepreneurial cultures [29], there is a growing demand for management decisions that allow for the environmental component to be taken into account in the formation of foreign economic policy, in particular in waste trade. At the same time, at the local level, the implementation of the circular model requires comprehensive management decisions, taking into account resource potential, institutional maturity and adaptability to environmental challenges [48].

Literary background

Plastic polymers are resistant to biological degradation and, when released into the environment, form micro- and nanoplastics that accumulate in aquatic ecosystems and food chains [42]. Since Thompson and others coined the term ‘microplastic waste,’ research into the impact of plastic waste on the environment has intensified significantly [51]. In addition to physical pollution, polymers contain chemical additives, including phthalates, stabilisers and dyes, which have toxic and endocrine-disrupting effects [18]. From an environmental point of view, plastic waste causes long-term pollution of soil, water and the atmosphere, and also affects public health. Many regions of the world are seeing an increase in cancer and reproductive diseases associated with plastic pollution [1]. It is predicted that by 2040, the volume of plastic waste could increase 2.5 times, jeopardising the achievement of the Paris Climate Agreement goals [53].

International trade in plastic waste remains an important economic and environmental challenge. A large group of scientists is investigating the economic drivers of international waste trade. International trade in plastic waste is driven by the demand for recycled plastic as a raw material [55]. Countries with developed manufacturing sectors but limited domestic plastic waste collection may import plastic waste to meet their needs [59]. The economic viability of recycling imported plastic waste depends on maintaining recycling rates above expectations [55]. Baran's study analyses cross-border flows of plastic waste from EU countries, highlighting the imbalance between export volumes and recycling capacities in importing countries [5].

In addition, the relationship between economic and environmental factors is analysed. Research by Loc et al. shows that, despite the economic benefits, trade in plastic waste poses risks to ecosystems, which can negatively affect the economies of countries that accept this waste [34]. The cyclical nature of the economy provides economic benefits through the expansion of international trade [11]. However, regions that lack adequate waste management infrastructure, including sorting, dismantling and recycling facilities, struggle to cope with the flow of imported plastic waste [31]; [49]. This can lead to environmental pollution through landfilling, incineration or illegal dumping [49]. Picuno et al. consider the potential of deposit return systems for plastic bottles as an alternative to international waste trade, which could reduce dependence on imports of recycled materials [44]. The introduction of biotechnological solutions in the field of plastic waste management is also considered a relevant direction. As noted in the

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study by Holei et al. [20], biotechnology can complement chemical processing and provide innovative mechanisms for breaking down polymers with less environmental impact, reducing dependence on export-import schemes.

A separate group of researchers is working on analysing the impact of regulations and restrictions in international trade, and the impact of restrictions on plastic waste imports introduced by China and other countries is being studied separately. For example, a study by Siyal and Ahmed (2025) analyses the consequences of introducing non-tariff barriers on the export of plastic waste, which leads to changes in global trade routes [47]. According to a study by de Assunção et al. [10], Chinese restrictions have significantly affected global plastic waste flows, forcing exporting countries to seek alternative markets, which has led to a redistribution of global waste traffic and increased environmental pressure on Southeast Asian countries. The study uses the Global Commodity Analysis (GCA) and ISM-MICMAC models to identify the main drivers of global trade in plastic waste [33]. Strict environmental regulations in developed countries increase the cost of household waste disposal, making it more economical to export plastic waste to countries with weaker regulations [36]; [56]. Amendments to the Basel Convention on Plastic Waste (BCPWA) were aimed at regulating trade in plastic waste from developed to developing countries, requiring prior notification and consent [22]. However, the effectiveness of such agreements depends on their compliance and the ability of importing countries to manage waste responsibly [8].

Thus, recent studies show that international trade in plastic waste is often a form of environmental colonialism, where rich countries dispose of their waste at the expense of vulnerable economies. This complicates the fight against global pollution and exacerbates inequality. International trade in plastic waste remains a controversial phenomenon that requires coordinated regulation and new economic mechanisms to ensure sustainable development.

Hypothesis: the world cannot digest the amount of plastic produced and consumed because the old structure of plastic waste trade has been destroyed. Traditional importers of plastic waste have begun to care about their own ecology and do not accept foreign waste. Thus, more and more plastic is being generated, and the world can no longer dispose of it using old methods.

The purpose of the article is to investigate the change in the global structure of world trade in plastic waste before and after the Chinese ban; to analyse the actions of the PRC to compensate for the shortage of plastic raw materials for domestic needs without imports; to classify countries of the world according to their adaptability to the export of plastic waste after the ban on imports to the PRC.

Research methods

The study is based on a combination of quantitative analysis of statistical data and clustering elements, which allows assessing the structural transformations in global trade in plastic waste before and after the introduction of the Chinese import ban in 2018.

The first stage involved a review and comparative analysis of data from international organisations, including the OECD, UNEP, ITC Trade Map and other open sources, on the volume of plastic waste generated, the level of recycling and the geography of trade. Particular attention was paid to the regional structure of waste generation, as well as the specific weight of exporting countries in global exports up to and including 2017.

In the second stage, the TFCR (Trade Flow Change Rate) indicator was constructed, which reflects the relative deviation in plastic waste export volumes after China's import ban, compared to the pre-ban period. The TFCR was calculated for 18 key exporting countries that supplied more than 100,000 tonnes of plastic waste to China in 2017. The base period covers 2008–2016; the transitional year 2017 was excluded as atypical. The indicator was calculated using the following formula:

$$TFCR_t = \left(\frac{TF_t - TF_{baseline}}{TF_{baseline}}\right) \times 100\ \%, \qquad (1)$$

where TF_t – the volume of exports in year t,
TFbaseline – the average annual volume of exports in the base period.

This allowed for a unified comparison of countries' adaptability, regardless of their initial export scale.

In the third stage, cluster analysis was used to typologise exporting countries according to the trajectories of their TFCR indicators in the period 2018–2022. Using the k-means method, countries were grouped into three clusters based on the similarity of changes in export flows. Prior to clustering, z-normalisation of annual data was performed to avoid the dominance of countries

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with large absolute export volumes. The optimal number of clusters was determined using the elbow method, based on inertia analysis (within-cluster sum of squares). Some countries, including Hong Kong and Mexico, were excluded from the analysis due to incomplete data or statistical atypicality.

In addition, graphical visualisation tools (diagrams, maps) were used to reflect changes in the structure of the global waste market after 2018, in particular the transition from a centralised disposal model (focused on China) to fragmented regional logistics.

The proposed approach made it possible to combine an empirical assessment of structural shifts in international waste trade with a classification of countries according to their degree of adaptability to external regulatory shocks.

Results and discussion

Plastic is a manifestation of progress and consumer convenience, but in order for the world to cope with current levels of plastic consumption, new ways of dealing with plastic waste and international trade in it are needed. Today, the most commonly used methods of plastic waste management in the world are recycling, incineration and landfill.

Landfilling is the most widespread and cheapest method of plastic waste disposal, which is a waste of resources and does not comply with the concept of sustainable development [6]. Landfilling involves removing huge areas from circulation, which is why most countries in the world face a problem with landfill sites. Landfills create the problem of intensive migration of toxic substances into the atmosphere and hydrosphere, and are therefore a source of environmental pollution [3].

Incineration is one of the most technically advanced methods of waste treatment, reducing the need for landfill disposal of plastic waste and allowing the generation of electricity and heat. The main disadvantages of this method are low efficiency and the formation of secondary toxic gaseous products from the combustion of plastic [3]; [6].

One method of recycling plastic waste is to reprocess it, i. e. convert it into granules, powder or crumbs, which can then be used either in their pure form or to produce composite materials. Among the existing recycling methods, physical, chemical and thermal methods are distinguished. Most contaminated plastic waste is more difficult to recycle using physical methods. To obtain high-quality, transparent, clean and homogeneous products, a series of processing and preparation steps are required, including sorting, shredding, washing, separating paper, labels and other impurities from the plastic, drying and processing by extrusion into granules. This method is costly and energy-intensive [3]; [6]; [17]; [38].

Chemical processing is a universal process that allows plastic to be converted into liquids and gases suitable for use as petrochemical products and raw materials for the production of polymer products through depolymerisation. For example, polyethylene terephthalate and polyamide can be depolymerised into monomers, purified by distillation and repolymerised. In this way, plastic waste becomes a cheap source of chemicals, including petrochemical products that can be used as fuel [3]; [6]; [50]; [38].

Examples of thermal processing include pyrolysis and gasification of plastic waste. These methods help to reduce landfill space and incineration costs, as well as helping to produce fuel or combustible gases from waste. As a result of thermal processing, gaseous products containing carbon dioxide, carbon monoxide, hydrogen, and methane are obtained from plastic waste, which can then be used for heating, lighting, and electricity generation. The advantages of these methods are the simplicity of the technology and economic efficiency [3]; [6]; [24]; [26]; [38]. Thus, recycling helps to reduce the high level of plastic pollution in the environment.

UNEP has presented a scenario for accelerating cyclical changes in plastic use through three actions to combat plastic pollution [53]:

1) Reuse: creating an enabling environment for the transition from a single-use plastic economy to a reuse society (will reduce plastic pollution by 30 % by 2040);

2) Recycling: accelerating the plastic recycling market (will reduce plastic pollution by 20 % by 2040);

3) Reorientation and diversification: creating a market for plastic alternatives (will reduce plastic pollution by 17 % by 2040.

In our study, we analyse current changes in the international environment with the aim of increasing effective plastic recycling. Plastic waste is generated unevenly around the world (Table 2). The further spread of plastic waste (which has not been effectively recycled in the countries where it was generated) only exacerbates the uneven distribution of its final disposal around the world.

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Table 2

Plastic waste generation by continent (2018–2023) [30]; [40]41; [53]; [62]

Continent	Plastic waste generation (million tons/year)	Key characteristics
Asia	145	Largest waste generator; large proportion of improperly disposed waste; export hub by 2018
Europe	62	High recycling rate (≈30%); EPR policy; high packaging consumption
North America	53	Highest per capita volumes; limited domestic processing
Africa	23	Low collection rates; open landfills and incineration; lack of infrastructure
Latin America	20	Active informal sector; low recycling rate
Oceania	3.5	Small volumes but high per capita generation; dependence on exports

By 2018, approximately 15–20 % of global plastic waste generated was exported [41]. According to the Harmonised Commodity Description and Coding System for foreign trade, plastic waste is classified under HS 3915: Waste, parings and scrap, of plastics. In the early days of the global plastic waste market, polyethylene (PE – ethylene polymers waste, parings and scrap) and polystyrene (PS – styrene polymers waste, parings and scrap) played a leading role in cross-border trade. Their popularity was due to their relative availability, ease of sorting and the possibility of re-granulation with low energy consumption. Over time, with the growth in waste generation, international trade has expanded to cover a wider range of polymers, including polyvinyl chloride (PVC – vinyl chloride polymers waste), polyethylene terephthalate (PET) and high-density polyethylene (HDPE). Each of these materials has different physical and chemical characteristics, which affects their recyclability, toxicological properties and economic feasibility of export. 40 % of imported waste is polyethylene (HS code 391510), 15% is polystyrene (391520), 13 % polyvinyl chloride (HS code 391530) and 32 % other plastics (HS code 391590).

Changes in the global structure of plastic waste trade – migrating waste

From 2016 to 2018, plastic imports fell from 15.4 million tonnes to 8 million tonnes, while China's imports amounted to 7.35 million tonnes in 2016. In other words, plastic waste was generated but could not be exported. From 2018 to 2025, the world has not yet formed a new system of international trade in plastic waste. Plastic waste continues to be generated by countries around the world that are unable or unwilling to recycle it themselves, but it is not being transported around the world. The world cannot recycle plastic waste.

Until 2018, the global structure of plastic waste trade was characterised by a high degree of centralisation, with China dominating as the main importer. More than half of all international plastic waste flows were directed to the PRC [46]. The main exporters in this model were the United States, the European Union countries, Japan, Canada and Australia. The centralised nature of the network allowed for economies of scale, but created a risk of systemic vulnerability by concentrating environmental pressure within a single market.

With the introduction of China's ban on imports of mixed plastic waste in 2018, the structure of global trade underwent significant changes. China completely banned imports of mixed plastic waste, citing the following reasons: low quality of imported plastic; toxic residues and chemical pollution; infrastructure overload. The centre of gravity has shifted to Southeast Asia, the Middle East, Africa and Latin America, leading to the fragmentation of clusters and the expansion of the geography of final processing. Instead, network density and coherence indicators have declined, indicating a weakening of coordination and an increase in the risks of unregulated disposal. New logistics and trade configurations have emerged, with no single dominant centre, but rather a regionalisation of flows. Figure 2 provides a graphical interpretation of the cluster structure of global trade in plastic waste before and after 2018.

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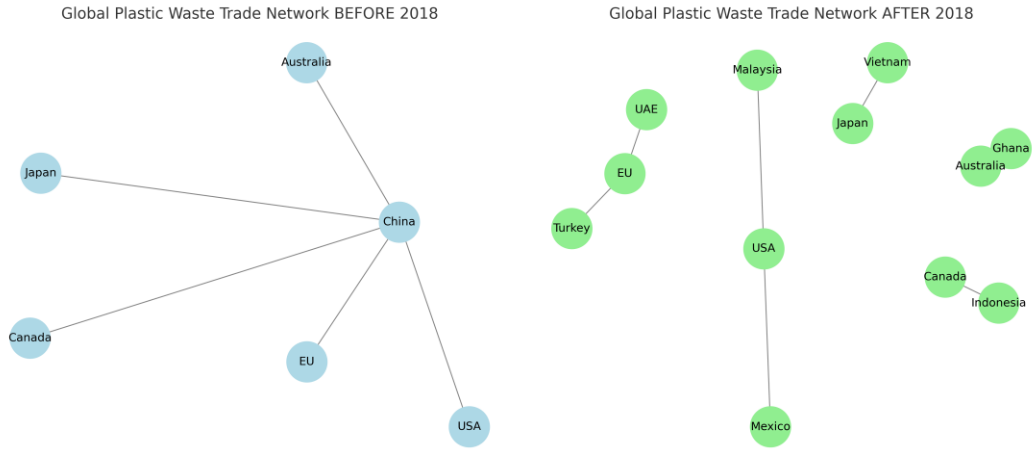

Fig. 2. Decentralizing the global plastic waste trade structure (AI)

The comparative diagram shows the transition from a centralised model (left), dominated by China, to a decentralised model (right), where numerous regional hubs are emerging. China's ban has created a radical shift in the global architecture of plastic waste trade. There has been a redistribution of risks, the creation of new 'waste zones' and the emergence of networks with lower levels of transparency.

The waste trade has partially shifted to Turkey, which has more than doubled its waste imports between 2017 and 2024. However, even in 2024, the volume of imports (about 0.678 million tonnes) was only a tenth of China's imports in 2017. There was also a reorientation of imports towards Southeast Asian countries: Malaysia, Vietnam, and Indonesia. However, Malaysia was only able to increase imports by 50 % to 0.873 million tonnes in 2018 and then even reduced them to 0.432 million tonnes in 2024 [23]. Indonesia saw similar import dynamics (imports in 2024 – 0.263 million tonnes). Vietnam has consistently increased its imports from 0.15 million tonnes in 2017 to 0.485 million tonnes in 2024. The role of informal recycling has also increased (Ghana, Nigeria, Senegal). In other words, pollution is being pushed out to weak countries (which do not have strict restrictions on waste imports). The fragmentation of international trade in waste leads to an increase in the cost of its processing, as the positive effect of scale in the centralised model no longer applies. This transformation leads to a decrease in the overall efficiency of the trading system. At the same time, the weak institutional capacity of new importers for environmental monitoring and control remains a significant problem, causing concern among international organisations and think tanks.

China after 2018

Under the centralised model, China imported recyclable plastic waste until 2018 to compensate for the shortage of domestic resources. Firstly, recycling imported waste consumes less energy and produces less waste than the primary production of similar materials. Secondly, China had relatively little incentive to collect its own plastic waste.

However, some importers used licences illegally. A number of environmental regulations were introduced to combat the illegal import of recyclable waste. These include the Green Fence (Lv Li Xing Dong) campaign in 2013, the National Sword (Guo Men Li Jian) campaign in 2017, and the Blue Sky (Lan Tian) campaign in 2018. As a result, the import of household plastic waste has been banned since 2018. The main reason for the ban was China's desire to better protect the environment. This sudden change in PRC policy is known as the 'China ban' or 'China shock' and has had a significant impact on the global trade in plastic waste [60].

China continues to increase its plastic waste recycling capacity, but efforts to increase the collection of its own plastic waste still do not cover the shortage of raw materials for recycling (Fig. 3). To fill the raw material gap caused by the ban, the Chinese government has introduced waste separation rules to increase the amount of recycled household plastic. China has also increased its use of virgin materials and imported recycled pellets. Some Chinese plastic waste recycling companies have relocated their plants to Southeast Asia, Japan and Taiwan and started exporting recycled pellets to China [60].

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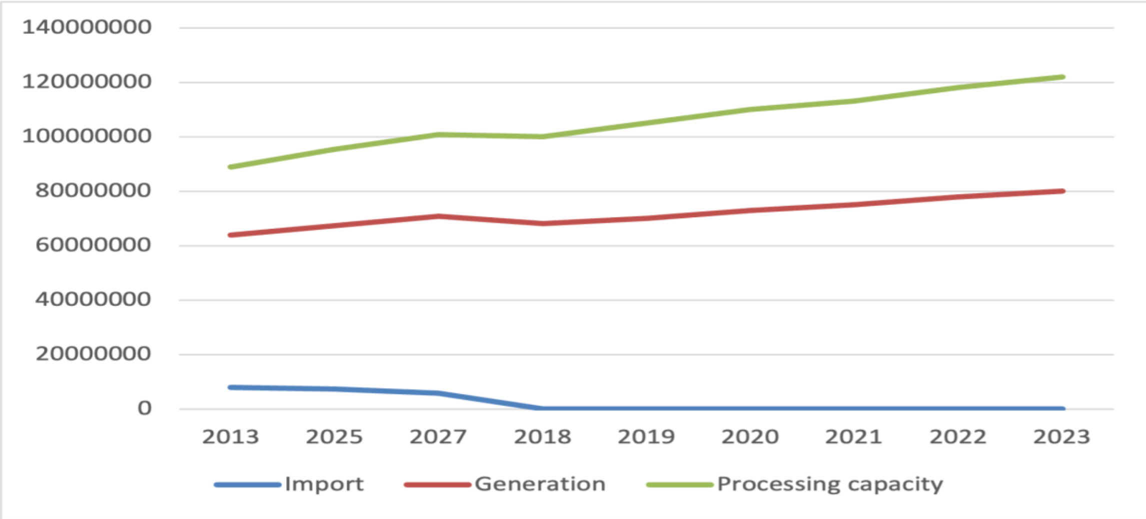

Fig. 3. Dynamics and ratio of imports, domestic generation and production capacity for plastic waste processing in the PRC (AI)

Clustering model of plastic waste exporting countries following the Chinese shock

As of 2017, the People's Republic of China remained the world's leading importer of plastic waste, as in previous years. According to official data, approximately 5.8 million tonnes of plastic waste were imported into the PRC in that year, 90 % of which came from 18 countries. This study only includes countries whose exports of plastic waste to China exceeded 100,000 tonnes per year (Fig. 4) [23]. Average imports to China from 2008 to 2016 amounted to 7.83 million tonnes, with minor changes in the structure by country. The centralised global model of plastic waste recycling has created a dependence of these countries on China, characterised by a share of exports to China and Hong Kong together ranging from 30 to 96 %. Export dependence in world trade is a negative phenomenon for trade in any goods, as the refusal of the dominant exporter to import has a negative impact on the economies of the exporting countries. In the case of export dependence on waste, the negative consequences are more noticeable in the environmental sphere [27].

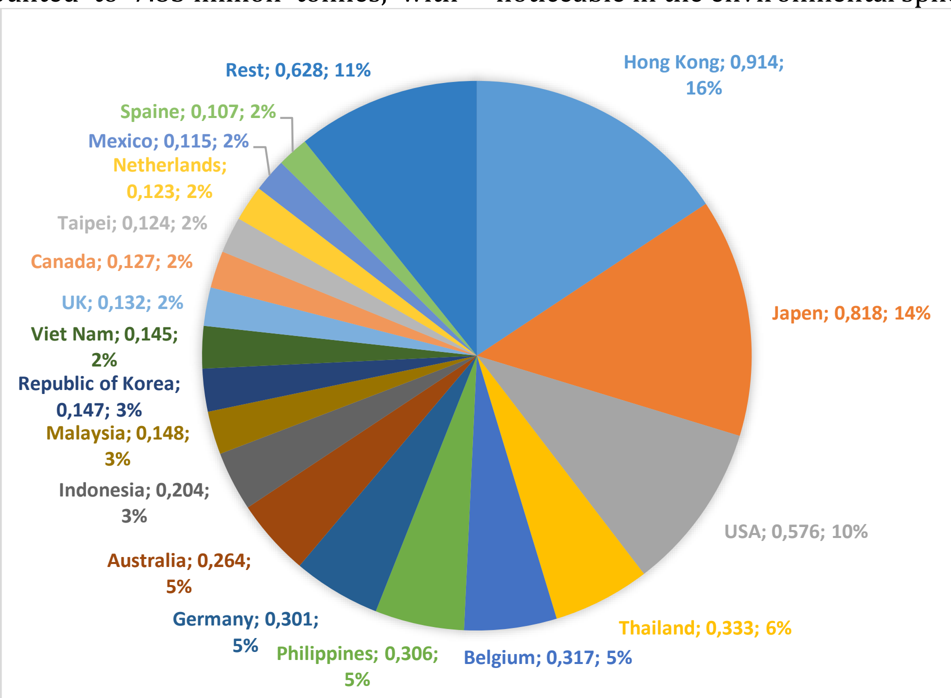

Fig. 4. Structure of imports of plastic waste into the PRC before the ban, tons, 2017

It should be noted that Hong Kong was the leader in the structure of plastic waste imports to the PRC. At the same time, plastic waste came from other countries to Hong Kong and then to mainland China, where Hong Kong is one of the most important transshipment ports for plastic waste in China [25]. When China banned imports, Hong Kong could no longer function as a re-

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exporter to China. Although in 2018 and 2019 it imported 0.6 million tonnes of plastic waste (and re-exported it to Malaysia, Thailand and Vietnam), in 2020 it halved its imports to 0.3 million tonnes, and in 2021 it left the market.

For a systematic analysis of the PRC's ban on plastic waste imports in the context of its impact on the ability to export waste from 'dependent' countries, we analysed the dynamics of changes in trade flow change rate (TFCR) of the above 18 countries until 2024. The TFCR indicator was calculated for 2018-2024 as the normalised change in each country's export volume relative to the average baseline (Fig. 5). We chose the period 2008–2016 as the baseline because in the summer of 2017, China announced a ban on waste imports from 2018, and the 2017 figures were already partially affected by it.

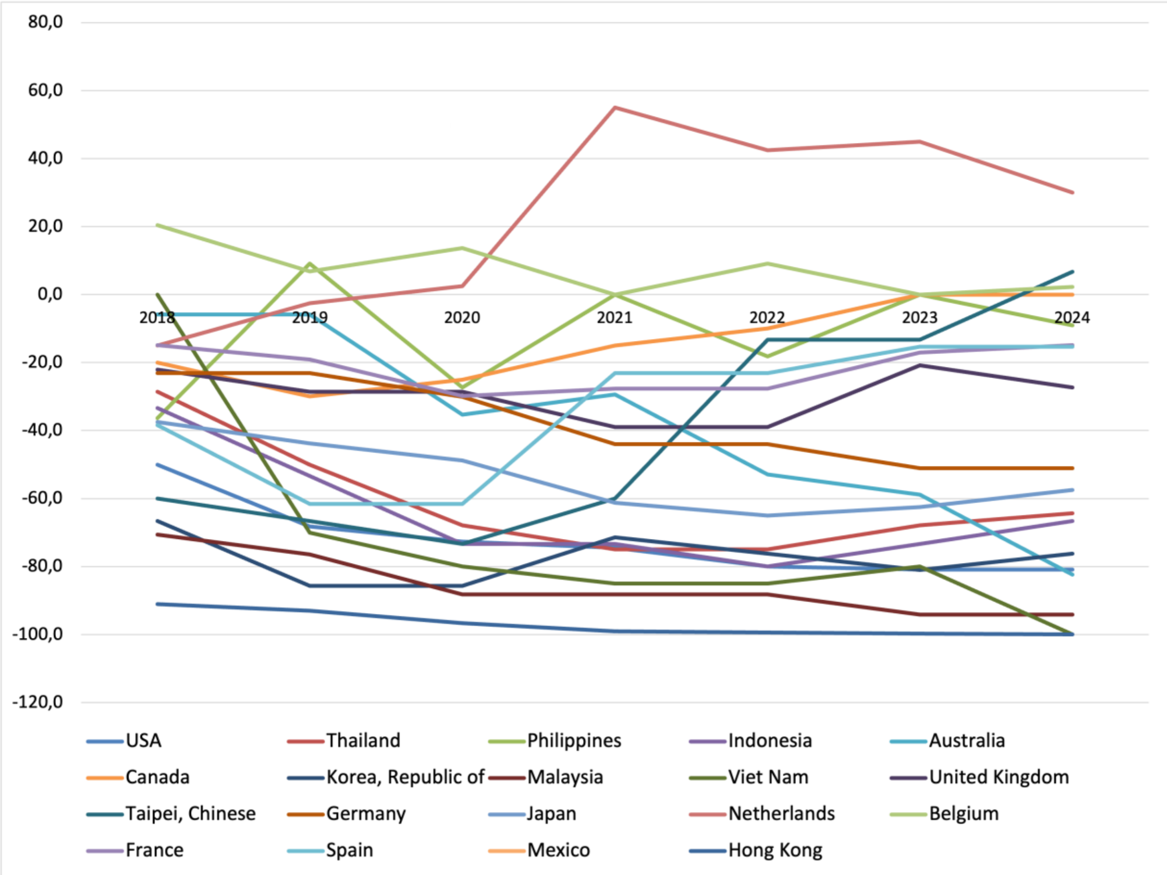

Fig. 5. TFCR dynamics of plastic waste in selected countries, 2018-2024

The main objective of the cluster analysis was to identify groups of countries with similar trends in adapting to the PRC ban during the period from 2018 to 2024. The K-means clustering method was used to classify countries according to the similarity of changes in the TFCR indicator in 2018–2024. To ensure a uniform scale of variables, Z-normalisation (standardisation) was applied for each year. This made it possible to avoid the dominance of variables with higher absolute values. Using the 'elbow' method, the feasibility of dividing into three clusters was justified (Fig. 6). This is the number after which the decrease in inertia slows down. Hong Kong was excluded from the clustering because it did not process waste independently and did not generate it in the quantities it exported. Mexico was also excluded because there is no export data for this country after 2017.

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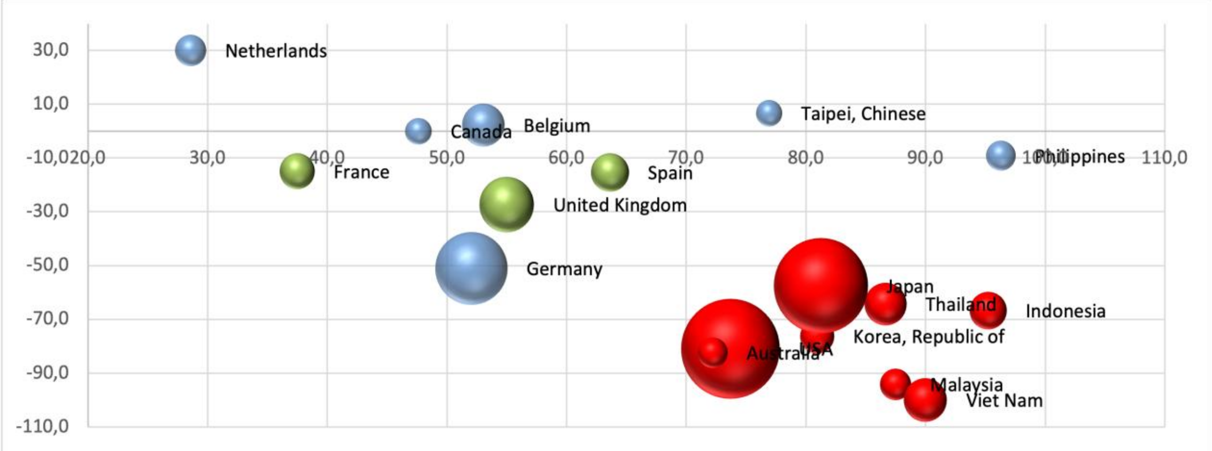

Fig. 6. Ranking of countries by degree of dependence on plastic waste exports to China (horizontal axis) and change in trade flows (TFCR, vertical axis) by 2024, %. The size of the ball depends on the volume of plastic waste exports to China in 2016
Red – first cluster, Blue – second cluster, Green – third cluster

Interpretation of results

The first cluster includes countries that have experienced a steady decline in TFCR throughout the entire period under review: the USA, Indonesia, Thailand, Malaysia, Australia, Korea, Vietnam, Germany, and Japan. This indicates a deep structural dependence of their plastic waste trade on the previously dominant market. This group shows a gradual decline in export volumes, with minimal signs of stabilisation even in 2024. This dynamic is associated with limited capacity to diversify export routes, insufficient adaptability of logistics chains, and internal legislative barriers that complicate the reorientation of exports. Indonesia, Korea, Vietnam, Malaysia, and Thailand have almost stopped exporting and have become net importers. Japan and Australia have reoriented their exports to the above-mentioned countries. The United States has been a net importer since 2020, reorienting its significantly reduced exports to Canada, Mexico, and, to some extent, Asian countries. Germany has also reoriented itself towards Malaysia, the Netherlands, Poland and Turkey.

The second cluster consists of countries with moderate TFCR dynamics, which, although they experienced declines in the first years after China's ban, are showing gradual stabilisation or even positive changes in export flows: the United States, Japan, Canada, Australia, the United Kingdom, and Spain. This indicates greater flexibility and more effective integration into new trade relations, in particular through re-export hubs or the development of their own infrastructure for sorting and preparing plastic waste for external markets.

The second cluster includes countries characterised by stable or growing TFCR dynamics, i.e. their export figures have not only recovered but exceeded pre-crisis levels: the Philippines, Taipei, the Netherlands, Canada, and Belgium. This indicates a relatively high capacity for adaptation, in particular through institutional support, expanded cooperation with old partners and new partnerships with countries that are deepening recycling. In 2016, Canada exported 50 % of its plastic waste to the United States, and since 2020, it has been exporting 90 % to the United States. Chinese Taipei is a net importer of plastic waste (from Japan and the Philippines) and has redirected its export flows to Malaysia and Vietnam. The Netherlands is a net importer and has redirected its exports to Indonesia and Vietnam, losing further export opportunities in the United Kingdom. The Philippines has redirected its exports to Taipei and Malaysia. Belgium has redirected its exports to the EU and Turkey. What these countries have in common is that their exports to China were small (up to 140,000 tonnes), which allowed them to reorient relatively quickly. The findings of this study reinforce a broader trend observed across global challenges: institutional preparedness and inclusive governance significantly determine how countries respond to systemic disruptions. This is echoed in recent research on gender disparity reduction, which shows that successful structural adaptation depends on cross-sectoral coordination and strong digital public management [28].

The third cluster consists of countries with a moderate decline in TFCR, which, however, have not been able to restore export flows. France, Spain, the United Kingdom. The United Kingdom has reoriented itself from an almost entirely Asian export market to Turkey and EU countries. Spain has been a net importer since 2018, and France has completely reoriented itself towards the EU. The countries in the third cluster have taken steps to limit plastic generation and have taken measures to restrict the use of plastics [15], [57].

Conclusions

Countries typically employ two approaches to address the issue of plastic waste generation: domestic recycling and export. Since China's ban has disrupted the established global system of export and recycling of plastic waste, and no effective solution through export has been found by 2025, global environmental tensions are increasing. On the one hand, the importance of a conscious attitude towards the use of plastic and the generation of plastic waste is growing. On the other hand, however, the world has already accumulated significant amounts of waste, and there are a huge number of plastic products in circulation that still need to be disposed of.

In previous publications, we noted that with a centralised recycling model, countries that import waste may eventually gain leverage over the world by refusing to dispose of or recycle it. But this has already happened. China has banned the import of plastic waste and halved the world's export capacity for plastic waste. As demonstrated in the article, even with an urgent need for such waste in the importing country (China), the presence of competitive advantages in terms of waste recycling and utilisation capabilities makes it possible to solve the problem of raw materials for recycling by stimulating and collecting its own waste.

The adaptive capabilities of plastic waste exporting countries proved to be rather weak. Only 5 of the 17 countries analysed managed to export plastic waste. However, these are countries with insignificant import volumes. Three other countries are trying to reduce plastic waste generation. The remaining nine countries with significant exports and plastic generation use an international trade model in which stronger countries have turned weaker countries into importers. However, in Southeast Asian countries, debates continue on a complete ban on imports of certain types of plastic waste and the tightening of restrictive policies.

Countries around the world must take responsibility for plastic recycling, even if it is carried out in other countries. The future of the world lies in chemical technologies for recycling plastic waste. Such technologies require investment, development and implementation in recycling facilities. The world cannot continue to dump waste in weaker countries with more lenient environmental standards. The current situation, where waste continues to be generated but cannot be recycled either in the country of origin or outside its borders, requires the controlled and responsible creation of global plastic waste recycling bases.

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