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From Waste Exports to Domestic Crisis: The Case of Waste Fires in Italy

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From Waste Exports to Domestic Crisis: The Case of Waste Fires in Italy[§]

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Abstract

In recent years, Italy's waste management infrastructure has shown signs of increasing vulnerability, including an increase in fires at treatment and storage facilities. This thesis investigates the relationship between plant pressure and fire incidence in Italy, in light of an exogenous shock of international significance, i.e., China's 2018 ban on waste imports. The analysis consists of two distinct parts. The first, through a panel regression with fixed effects, tests whether the ban resulted in an increase in the volumes of waste treated at the municipal level. The results, while indicating a positive relationship, are not statistically significant. The second part analyzes the relationship between plant operational load and the number of fires, using the two-stage hurdle model. A positive and significant effect of plant pressure on fire incidence and intensity is found. The results show that, regardless of whether the increase in treated waste can be attributed with certainty to the Chinese ban, plant overload is a real risk factor. A set of policy recommendations is also provided, based on empirical findings and a descriptive analysis of public spending on waste management. This thesis therefore emphasizes the need to strengthen the resilience of the national waste system through a more balanced distribution of treatment capacity, improved operational monitoring, and the introduction of targeted prevention tools. Finally, it proposes to extend the analysis to more granular data and explore the economic and environmental implications of fires to effectively inform public policy in the sector.

Keywords: Waste management, Fires at waste facilities, China waste import ban, Negative binomial regression, Hurdle model.

J.E.L. classification: Q53, Q58, H76, C23, C25, L98.

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Contents

1 Introduction

In recent years, waste management has emerged as a major environmental and logistical challenge globally. The intensification of municipal and special waste flows, the growing need for treatment facilities, and the necessity to ensure traceability and legality in disposal processes have pushed national and international institutions to adopt increasingly complex and integrated strategies. In this context, one systemic event that has marked a turning point in global waste management dynamics is certainly the *National Sword* policy, i.e., China's ban, effective on January 1, 2018, on the import of several categories of solid waste, including especially plastics and special waste. This measure has generated a sudden exogenous shock to the international disposal system, disrupting a balance previously based on the outsourcing of flows to third countries and triggering a structural crisis in the treatment chains of exporting countries, including Italy.

Waste management sits at the intersection of environmental needs, market logic, and institutional responsibilities. In a context of increasing pressure on infrastructure systems, ensuring the resilience and sustainability of treatment and disposal networks becomes essential to prevent environmental and health crises. Disruptive events, such as the one represented by the Chinese ban, highlight the structural vulnerabilities of the system, showing how crucial the smooth operation of these facilities is to the stability of the overall socio-economic system.

Italy is a country traditionally dependent on exports for the disposal of a significant portion of its waste, especially plastic and special waste, and has found itself particularly exposed to the effects of the radical change represented by the Chinese ban. Indeed, in the Italian context, characterized by strong territorial heterogeneity, limited plant capacity, and fragmented multilevel governance, the effects of this shock have been particularly evident. This institutional fragmentation leads to inconsistency in the ability to respond to critical phenomena, and makes it particularly difficult to implement coordinated risk prevention and management strategies. The need to redirect previously exported flows within the national territory has increased pressure on treatment and disposal facilities, generating a number of critical operational, environmental, and institutional issues. Among these, the increase in the number of fires occurring at waste management facilities has drawn attention, raising questions about the possible link between plant overload and structural vulnerability of the supply chain.

In this thesis my goal is to empirically investigate the relationship between increased pressure on facilities, defined as the amount of waste treated, and the incidence of fires recorded at these facilities, testing in particular whether the exogenous shock represented by the Chinese ban has contributed to increasing the risk of critical events in the Italian system. To this end, a new original municipal-level database has been constructed for the period 2016-2020, combining information on waste treatment and disposal facilities, geolocated data on fires that have occurred at these facilities, and structural control variables. To empirically investigate the possible link between plant pressure and increased fires, the analysis consists of two main parts. The first part consists of a panel regression with fixed effects at the municipal level, aimed at testing whether the 2018 Chinese ban actually generated a significant increase in waste treated at the local level. This analysis is an essential preliminary step to validate the hypothesis of an exogenous shock to the system's operational capacity. Instead, the second part focuses on the relationship between plant pressure and fire incidence adopting a two-stage hurdle model: the first stage estimates the probability that a facility will record at least one fire, while the second analyzes the number of fires conditionally on exceeding the threshold. This approach allows the determinants of fire occurrence to be distinguished from those that influence fire intensity, offering a more detailed interpretation of the phenomenon.

Recent literature has stressed how structural vulnerabilities in waste management systems are closely linked to plant overload, illicit disposal practices, and weak institutional capacity (Mikalsen et al., 2021; Legambiente, 2022; Agovino et al., 2023). Studies have shown that facility congestion increases the risk of both spontaneous and criminal fires, while the lack of transparency in waste flows facilitates illicit practices (INTERPOL, 2020). Further evidence from other European contexts highlights the systemic consequences of uncontrolled waste fires and the importance of effective monitoring and governance (Nadal et al., 2016; Kuta et al., 2023). However, despite these contributions, there is still no quantitative analysis directly assessing whether systemic shocks, such as the 2018 Chinese import ban, translate into an observable increase in fire risk. This thesis builds upon these strands of research while filling this critical gap. This thesis therefore aims to contribute to the existing literature by offering a quantitative perspective on a phenomenon that is still little studied as a whole, providing empirical evidence that is useful both for the design of more effective environmental policies and for strengthening the resilience of the national waste management system.

The empirical results confirm that while the immediate effect of the Chinese ban on treated volumes in Italy is not statistically significant, sustained plant pressure is robustly associated with an increased likelihood of fire incidents. Specifically, the analysis shows that higher volumes of treated waste significantly raise both the probability of experiencing at least one fire and, conditionally, the expected number of fires at facility level. These findings highlight a systemic fragility in the Italian waste management system, where congestion and structural imbalances translate into higher operational risks. Thus, these results might offer useful insights to guide strategies to strengthen the ability of the Italian system to respond to sudden shocks, helping to identify preventive interventions and promote a more efficient allocation of public resources across the territory.

The thesis is structured as follows: Section 2 provides the international context of the analysis, describing the 2018 Chinese ban on waste imports, its global implications, and the subsequent reconfiguration of European and Italian waste exports; Section 3 turns to the Italian waste management system, discussing its regulatory and regional structure, the disruptions caused by the ban, and the phenomenon of fires at waste facilities, complemented by a review of the relevant literature on facility pressure, fire risk, and illicit waste management; Section 4 presents the empirical analysis, detailing the construction of the dataset, the definition of key variables, and the methodological strategy, before illustrating the results of the two parts of the econometric investigation; Section 5 expands the discussion by contextualizing the empirical findings within broader public investment patterns in environmental protection and formulates policy recommendations aimed at improving system resilience; and finally, Section 6 concludes by offering further reflections on policy implications and future developments of the research.

2 Waste Trade Reconfiguration after China's Import Ban

China's ban on imports of recyclable waste from around the world, which came into effect in 2018, suddenly disrupted the established balance in transboundary waste disposal chains. The closure of the main outlet outside the EU and the subsequent reallocation of waste flows have highlighted the asymmetries in disposal capacities in Europe. For Italy, which is structurally exposed abroad for the treatment of significant quantities of waste, the shock has resulted in a more intense internalization of flows, with immediate effects on storage times, plant saturation, and treatment capacity. The interaction between these factors and key characteristics of the Italian waste management system, such as territorial heterogeneity, authorisation constraints, and institutional fragmentation, has increased operational pressure, while raising issues of traceability and control along the supply chain.

In the European context, the reallocation of waste flows has followed partially divergent trajectories: on the one hand, the domestic uptake of fractions previously exported, and on the other hand, the consolidation of intra-EU hubs with greater capacity and higher standards. Italy, however, unable to absorb the new increased quantities in the domestic market, has had to increase its dependence on waste exports to other European countries. For Italy, this has resulted in longer delivery times, higher stock levels, and greater pressure on domestic treatment and storage facilities, also affecting operational organization.

The following sections provide further details on this picture. Section 2.1 reconstructs the Chinese ban and its immediate effects on trade, clarifying the link between regulatory shock and the reorganization of flows. Section 2.2 analyzes the resulting reallocation within Europe, with particular attention to the paths through which this dynamic has spilled over into the Italian system, especially in terms of disposal options. Finally, it is worth clarifying that, although starting from an international event, the focus of the entire thesis will remain on Italy, in an attempt to understand how the changed external context resulted in concrete effects at the domestic level.

2.1 China's Ban on Waste Imports

In recent decades, the increase in global production of municipal solid and special waste has made its management a central issue in international debate. In this context, China has long played a dominant role as the world's main hub for the import and processing of recyclable waste, particularly plastics, paper and metals. Between 1992 and 2016, China imported about 106 million tons of plastic waste, accounting for 45% of global exports of these materials (Brooks et al., 2018). This model of transboundary waste management, based on offshoring treatment to countries with lower environmental standards, was based on the logic of comparative advantages. By outsourcing to countries with more permissive regulations, such as China, most industrialized Western countries were able to overcome the high environmental and regulatory costs associated with treating domestic waste. In return, China received low-cost materials to recycle, useful for fueling its own manufacturing expansion, particularly in the plastics and chemicals sectors. This system thus created a balance of economic advantages, but based on strong environmental asymmetries between the countries involved.

However, this balance was broken by the adoption of China's policy known as the *National*

Sword, which came into effect on January 1, 2018. The People's Republic of China banned the import of several categories of waste by introducing an extremely stringent purity threshold: waste shipments could contain no more than 0.5% foreign materials, i.e., impurities that did not meet recyclability criteria. This limit was officially notified by China to the World Trade Organization in July 2017, announcing the introduction of strict restrictions on the import of 24 categories of waste, including contaminated plastics (World Trade Organization, 2017). The measure was described by industry players as technically almost unachievable, leading to the practical impossibility for many Western exporting countries to meet the new required quality standards (Lin et al., 2023). This resulted in a systematic rejection of most shipments destined for China and a drastic redesign of global plastic waste streams (Wen et al., 2021).

Two major motivations underlie this regulatory shift. First, the growing environmental and health degradation related to informal and poorly controlled imported waste disposal practices. Second, China's strategic interest in reorienting its industrial model by reducing dependence on contaminated raw materials and incentivizing the adoption of higher quality standards in production. The new strategy, therefore, is part of a larger pattern of environmental and industrial reforms (Li et al., 2024).

The consequences of this decision spread rapidly throughout the global recycling supply chain, generating an exogenous regulatory shock. Countries such as the United States, the United Kingdom, Germany and Italy, which have traditionally relied on China for waste management, have experienced a buildup of plastics and increasing pressure on their domestic systems. According to the OECD (2022a), global plastic waste exports declined by about 40% between 2017 and 2018, a phenomenon well documented in Figure 1, while a redistribution of flows to Southeast Asian countries (Malaysia, Vietnam, Indonesia) took place simultaneously, as highlighted in Figure 2. However, these countries lacked equivalent infrastructure and subsequently imposed similar restrictions[1].

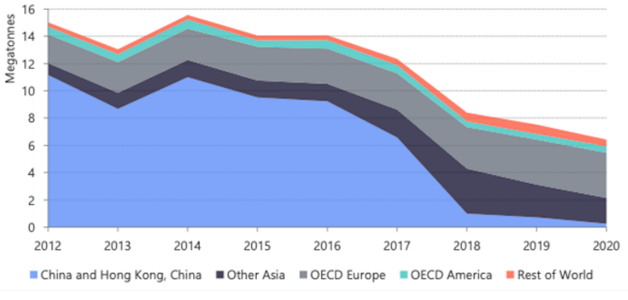

Figure 1: Global reported exports of plastic waste and scrap by weight and destination (2012-2020). *The figure shows the global decline in plastic waste exports between 2017 and 2018 as a result of the National Sword Policy. Source: OECD (2022a).*

Figure 2: Monthly reported exports of HS 3915 by weight (in thousand tonnes) for 2016-2020. *The figure shows the redistribution of plastic waste (HS 3915) exports to Southeast Asian countries after the Chinese ban. Source: OECD (2022a).*

The quantitative evidence of this shift is confirmed by Figure 3, which shows a dramatic decline

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[1] For example, Malaysia, Thailand and Vietnam have all implemented waste import restrictions during 2018 (OECD, 2022a).

in Chinese imports of waste plastics (HS 3915) between 2010 and 2020. Until 2016, China was steadily importing over 7 million tons per year. In 2017, there was a reduction to about 5.8 million tons, while in 2018 imports collapsed to only around 51 million kilograms, which is about 0.6% of the 2016 level. The trend thus shows a clear structural break, indicative of the severity and immediacy of the regulatory intervention.

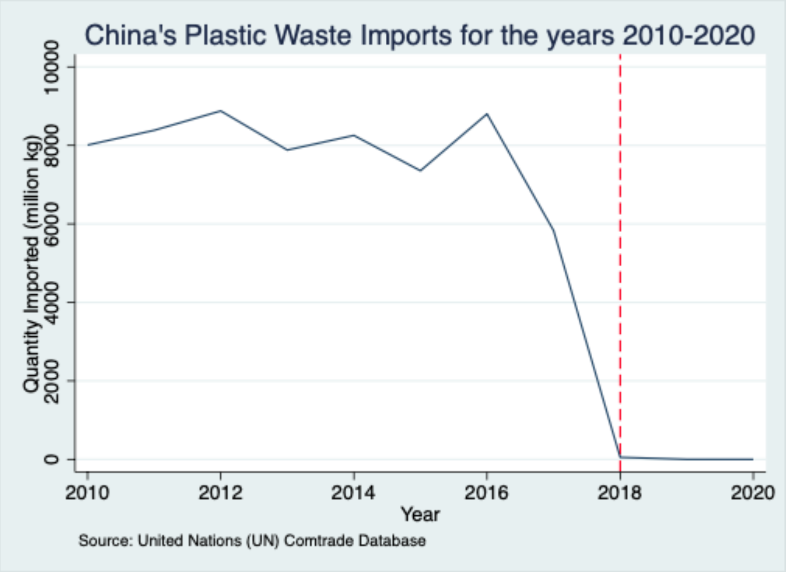

Figure 3: China's Plastic Waste Imports for the years 2010-2020. *The figure illustrates the significant drop in plastic waste imports by China after the 2018 ban. Source: United Nations (UN) Comtrade Database, https://comtradeplus.un.org (processed dataset).*

The impact of the Chinese ban has also had significant implications at the European level. The European Union, recognizing the vulnerability resulting from dependence on extraterritorial waste management hubs, has initiated a series of reforms aimed at strengthening domestic processing capacity and reducing overall environmental pressure. In particular, a major revision of *EC Regulation 1013/2006* (European Commission, 2021) on transboundary shipments of waste was undertaken, which regulates the movement of waste between EU member states and between the EU and third countries. This regulation, incorporating obligations under the *Basel Convention*[2], aims to ensure that exported waste is treated in an environmentally sound manner, giving priority to recovery and management in facilities that meet high environmental standards. In response to new critical issues that have emerged as a result of China's *National Sword Policy*, the European Commission submitted a proposal for a substantial revision of the regulation in 2021. Key changes include: (1) a ban by 2026 on the export of plastic waste to non-OECD countries unless they can demonstrate that they are managing it according to environmental criteria equivalent to European ones, and (2) the mandatory introduction of digital shipment tracking systems, aimed at improving flow control, preventing illegal trafficking

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[2] The *Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal*, adopted in 1989 and entered into force in 1992, is the main international treaty regulating the transfer of hazardous wastes and other wastes between countries. Its main objective is to protect human health and the environment by minimizing the generation of hazardous waste, ensuring its environmentally sound management, and fighting illegal trafficking. The Convention severely restricts the export of hazardous wastes from developed to developing countries and promotes waste minimization, treatment and recycling.

and increasing transparency in the sector (European Parliamentary Research Service (EPRS), 2022). These reforms are part of a broader strategy promoted by the *European Green Deal* (European Commission, 2019) and the *Circular Economy Action Plan* (European Commission, 2020), which aims to reduce dependence on external disposal solutions, enhance domestic capacity for recycling and materials treatment, and consolidate the Union's strategic autonomy in the field of waste management.

The impacts of the ban have also been examined in depth in academic publications. Sigman and Strow (2024), for instance, analyze the impact of the ban on the entire municipal solid waste management system in the United States, noting an increase in landfilling and a decline in post-consumer recycling activity, confirming the claim that waste trade restrictions can transfer environmental damage to exporting countries. Brooks et al. (2018) estimate that, in China's absence, about 111 million tons of plastic waste will find uncertain locations by 2030. Wen et al. (2021) show how relocation of flows to less industrialized countries results in a net increase in greenhouse gas emissions in the short run, due to inefficient facilities and increased transportation impacts. These results highlight not only the direct environmental consequences, but also the systemic implications of reconfiguring international disposal chains.

In conclusion, the Chinese ban from 2018 is an unparalleled exogenous regulatory shock to the World waste management system. Its repercussions extend far beyond environmental implications, involving economic and logistical dynamics on a global scale. The magnitude of this event provides the framework for the analysis proposed in the following chapters, aimed at examining the downstream effects of the ban on the Italian waste management system.

2.2 European and Italian Waste Exports

In the past few years, the dynamics of waste exports in Europe and Italy have undergone major transformations, reflecting not only the impact of global environmental policies but also the growing need for more sustainable and responsible management of materials. Throughout history, the European Union has emerged as one of the world's leading exporters of plastic waste, outsourcing much of its flows to third countries, prompted by lower treatment costs and less stringent environmental regulations. Prior to the last 20 years, European exports of waste, particularly plastic waste and electronic materials, were the main strategy for managing domestic surpluses. Exports were heavily directed to East Asian countries, primarily China, which offered lower treatment costs and less rigorous environmental regulations (Brooks et al., 2018). As a result, European countries were able to lower their domestic operational expenses by outsourcing the environmental effects of disposal. However, the lack of tight controls in destination countries often led to unsafe treatment practices, resulting in local environmental damage (Velis, 2014). Over the years, growing waste accumulation and deteriorating environmental conditions in importing countries have fueled international tensions and pushed for a global review of waste trade practices. The ban imposed by China in 2018 marked a historic break in this model, highlighting the fragility of a system based on dependence on external markets.

As Europe's environmental policies have evolved, a greater awareness of the implications of such practices has emerged, culminating in a push for a reduction of unsustainable exports. In particular, since 2018, European waste exports have shown a substantial shift: following the closure of traditional

Asian markets, such as China, a reallocation of flows has occurred, with significant growth in exports to countries such as Turkey, India and some North African states. At the same time, there has been an increase in intra-EU shipments, with a concentration of flows to countries with more advanced recycling infrastructures, such as Germany, Belgium, and the Netherlands. As highlighted in Figure 4, indeed, Turkey emerges as the leading destination country for waste from the European Union in 2022, with about 12.4 million tons received, followed at a distance by India (3.5 million tons) and the United Kingdom (2 million tons).

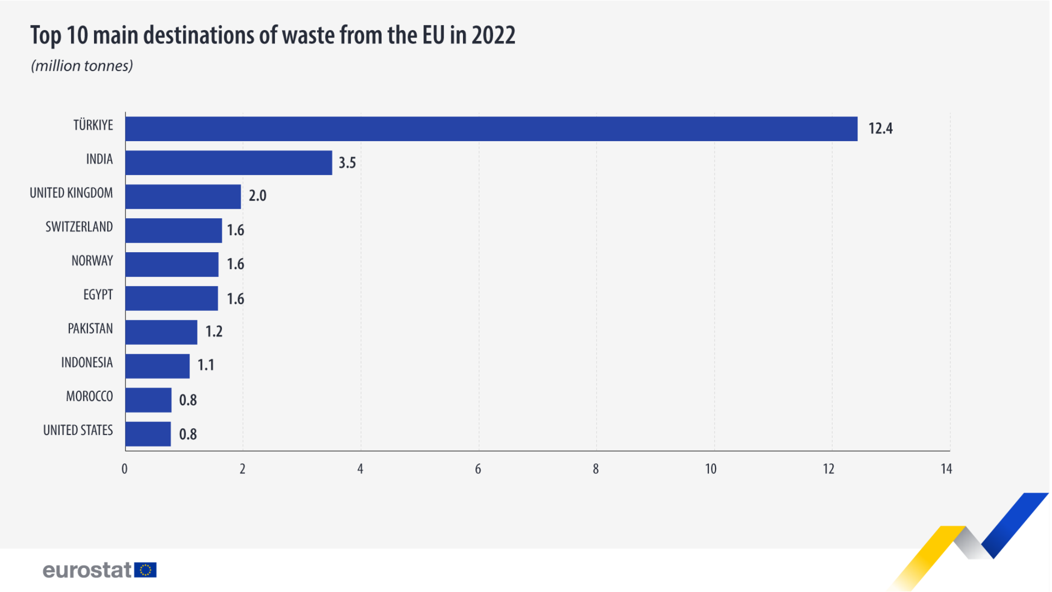

Figure 4: Top 10 main destinations of waste from the EU in 2022. *As the figure shows, Turkey is one of the new main destinations for European waste. Source: Eurostat, https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20240118-1.*

This shift has raised new critical issues. On the one hand, inequalities among member States in terms of treatment capacity have become more pronounced. Some European countries have become new recycling hubs capable of handling waste from States with less efficient systems. On the other hand, increased exports to non-EU countries have raised concerns about waste treatment standards in those places, which are sometimes lower than those in Europe, and environmental impact (Thapa et al., 2024). The European Union has been forced to reevaluate its management approach and move towards more self-sufficient policies due to rapid changes in waste streams. For this reason, a significant revision of *EC Regulation No. 1013/2006* (European Commission, 2021) on waste shipments has been proposed, highlighting the importance of limiting waste exports and strengthening traceability of flows, as well as reaffirming the principles of the circular economy with the *European Green Deal* (European Commission, 2019) and the new *Circular Economy Action Plan* (European Commission, 2020). However, the goal of limiting exports has increased infrastructural differences between member States. The growing number of waste shipments within the EU, in particular, points out how recycling capacities are concentrated in a few countries, resulting in an internal treatment market that does not always provide ideal solutions from an environmental point of view.

Within Italy, waste exports have undergone major transformations. According to ISPRA (2020), Italy exported about 430,000 tons of plastic waste in 2019, with main destinations being Turkey and, to a lesser extent, Malaysia. As shown in Figure 5, instead, Italy's exports of special waste in 2019 were mainly to European countries, particularly Germany, Austria and France, with a significant flow to Turkey as well (ISPRA, 2021). The graph also shows that the share of non-hazardous waste exported was significantly higher than that of hazardous waste, underscoring the growing relevance of the foreign market for the management of less complex but high-volume portions of waste. This dynamic confirms Italy's structural dependence on foreign markets, emphasized by domestic infrastructure deficiencies, especially in the South.

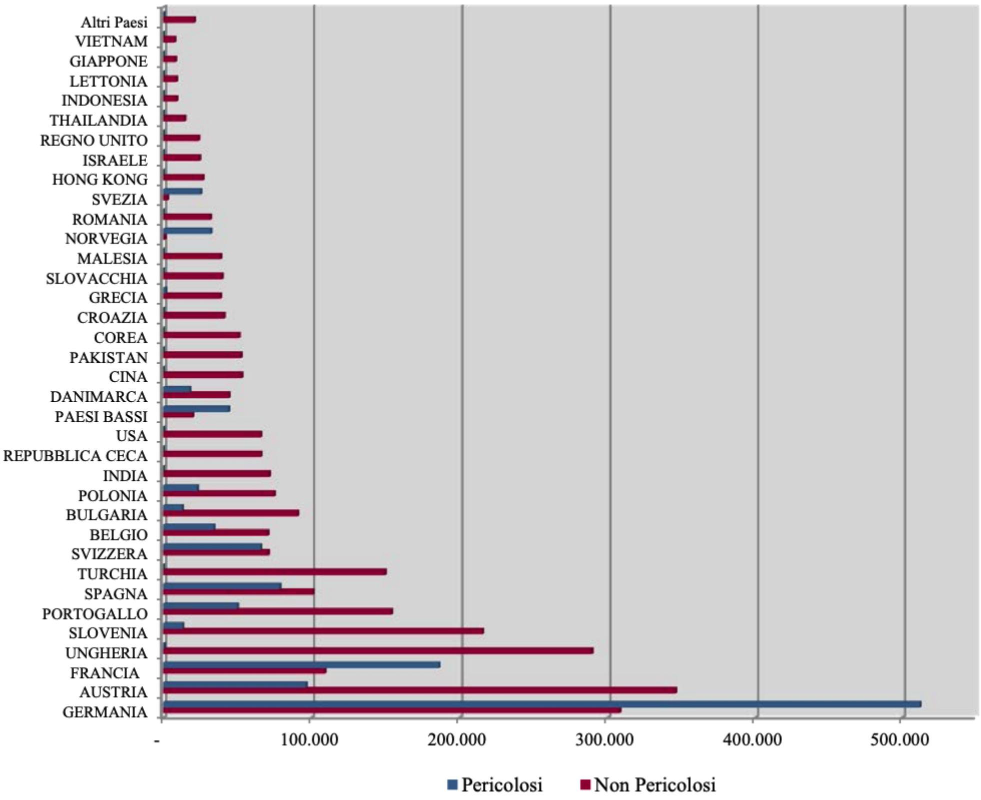

Figure 5: Special waste exported from Italy by country of destination (tons), year 2019. *The figure shows that Italy's exports of special waste in 2019 were mainly to European countries. Hazardous waste is shown in blue, while non-hazardous waste is shown in red. Source: ISPRA (2021).*

In addition to these issues, there is the matter of traceability and legality of flows. Recent episodes of illicit waste trafficking to foreign destinations have highlighted critical issues in monitoring systems, with exports of mixed and contaminated waste disguised as materials for recycling (Baldé et al., 2024). According to the INTERPOL (2020) report, there has been a considerable increase in illegal waste shipments in recent years, mainly redirected to Southeast Asia via transiting countries to disguise their origin. The report also documents an increase in illegal waste fires and landfills in Europe and Asia, as well as widespread use of counterfeit documentation and fraudulent registrations, outlining a complex global picture that requires targeted enforcement responses.

The analysis of recent dynamics shows that the issue of waste exports cannot be addressed through strengthening trade restrictions alone. Action is needed on several levels: strengthening domestic processing infrastructures, developing advanced recycling technologies, strengthening customs controls, and implementing effective extended producer responsibility mechanisms[3].

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[3] The principle of Extended Producer Responsibility (EPR) is a regulatory and management approach under which producers of goods are also responsible for the post-consumer phase of the life cycle of their products. Specifically, they are

3 Waste Management System, Disruptions, and Fire Risk

In the Italian waste management system, the distinctive institutional structure and limited plant capacity have contributed to exacerbating the effects of the Chinese shock. Particular attention should, indeed, be paid to the phenomenon of waste fires as an indirect consequence of the increase in pressure on Italian facilities. To this end, Section 3.1 reconstructs the regulatory and institutional framework and documents the main territorial differences and recent policy interventions. Section 3.2 analyzes the disruptions that have affected the waste management chain, with particular attention to the domestic effects of the 2018 shock in terms of capacity, logistics, and traceability. Section 3.3 presents the empirical setting of fires at Italian plants, highlighting their temporal and geographical dynamics and their link with overload conditions and governance issues. Finally, Section 3.4 summarizes the literature on plant pressure, fires, and illegal practices, identifying the theoretical mechanisms and knowledge gaps that guide the subsequent empirical analysis.

3.1 The Italian Waste Management System

Waste management is one of the fundamental pillars of modern environmental policies, closely linked to land protection, public health, the fight against climate change and the promotion of a more sustainable economic model based on the principles of circular economy. Growing urbanization, increasing consumption, and accelerating industrial processes call for waste management systems that are efficient, equitable and resilient. The strategic importance of an effective waste management system has been emphasized internationally by documents such as the European Commission's *Circular Economy Action Plan* (European Commission, 2020), which, as mentioned above, places efficient resource management at the heart of the ecological transition. In addition, the *United Nations 2030 Agenda for Sustainable Development* (United Nations, 2015) identifies waste management as a key element in achieving several Sustainable Development Goals (SDGs), particularly those related to sustainable cities, responsible consumption and production, and protection of terrestrial and marine ecosystems.

In Europe, the discipline of waste management has undergone a radical evolution from the 1970s to the present, culminating in the definition of a management hierarchy based on priorities: prevention, preparation for reuse, recycling, energy recovery and, only as a last resort, disposal. Italy has adapted to this European framework by gradually incorporating EU principles and building a complex, multilevel regulatory system. The legal foundation of waste management in Italy is represented by *Legislative Decree No. 152 of April 3, 2006* (*Testo Unico Ambientale*, i.e., *Consolidated Environmental Act*, Italian Republic, 2006), which coordinates the main environmental regulations and implements European directives, including *Directive 2008/98/EC* (*Waste Framework Directive*, European Parliament and Council, 2008), later amended by *Directive 2018/851/EU* (European Parliament and Council, 2018). The Framework Directive establishes a common European legal framework for the management and treatment of waste to protect the environment and human health, introducing the principle of the waste

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required to take responsibility, financially or operationally, for the collection, treatment, recycling or disposal of products once they become waste. This mechanism incentivizes companies to design products that are more durable, reusable and easily recyclable, thus promoting the transition to a circular economy.

hierarchy. Priority is given to prevention, followed by preparation for reuse, recycling, other recovery (such as energy recovery) and, only as a last option, disposal. This hierarchy is aimed at minimizing overall waste generation and promoting the maximum recovery of useful resources. Recent analyses of local waste management policies in Italy, however, have shown that while formally adopting the European waste hierarchy, practical applications may produce limited environmental results if not accompanied by adequate assessment and monitoring tools (Camana et al., 2021). Member States need to strengthen legislative measures to ensure environmental and health protection, promote extended producer responsibility, ensure safe management of hazardous waste, and encourage the creation of an integrated network of treatment facilities, reducing dependence on transboundary shipments.

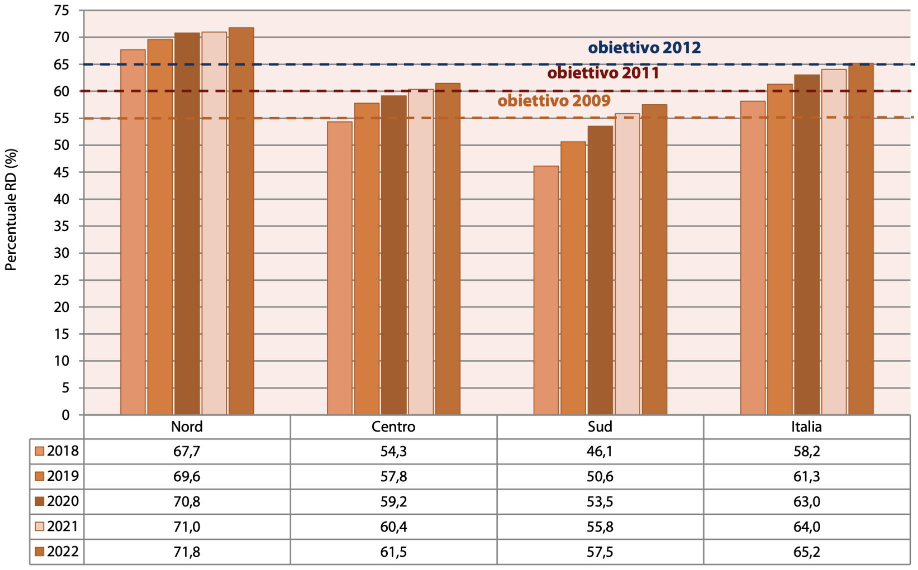
The *Consolidated Environmental Act* (CEA) regulates in detail the authorization requirement for anyone wishing to carry out waste treatment operations, defining tight criteria regarding the type and quantity of waste treated, the management methods adopted, and monitoring and control measures. In particular, it is required that hazardous waste should be treated under conditions that protect the environment and human health, preventing contamination and ensuring proper labeling and traceability. In addition, the legislation promotes the establishment of separate collection systems for specific materials such as paper, plastics, glass and metals, which are essential to facilitate high-quality recycling and reduce the amount sent for disposal. More specifically, the *Consolidated Environmental Act* establishes that all waste management activities must be authorized by the competent authorities, after verification of the technical and administrative conformity of the proposed operations. In Italy, by competent authorities is meant primarily the regions, which issue permits for waste management activities. However, in many regions these administrative functions are delegated to provinces or subregional authorities, as set by *Article 197 of the Consolidated Environmental Act*, thus ensuring a multilevel articulation of the authorization system. The CEA also stipulates the obligation for operators to maintain waste loading and unloading records and to report data annually through the *Consolidated Environmental Declaration Form* (i.e., MUD, *Modello Unico di Dichiarazione Ambientale*). Waste must be identified through appropriate classification (EWC, *European Waste Catalogue*, European Commission, 2000) and treated differentially according to its hazardous characteristics. Special attention is paid to the management of special wastes and hazardous wastes, for which specific procedures for temporary storage, transport, and treatment are provided in order to minimize environmental risks. Finally, the CEA establishes that landfills are subject to specific technical requirements for sealing, emission control, and post-closure management, in line with the principles of *Directive 1999/31/EC* on waste landfills, later amended by *Directive (EU) 2024/1785* (Council of the European Union, 2024).

Given this general regulatory framework, it is crucial to understand how Italy has structured its waste management system in terms of the division of institutional responsibilities, which are spread among the State, regions and local authorities, with distinct but complementary roles. The Italian waste management system has three institutional levels, outlining a multilevel structure that seeks to ensure consistency with European principles. These three levels are the state, regions, and local governments. The state plays a central role in determining the overall regulatory framework, transposing European directives and establishing the basic criteria for waste management. In addition, the state approves national strategic plans, such as the *National Waste Management Program* (i.e., *Programma Nazionale per la Gestione dei Rifiuti* (PNGR), Ministry of Ecological Transition, 2022), and coordinates goals for landfill reduction, recycling, and energy recovery on a national scale. Through the *Ministry of Environment and Energy Security*, it exercises policy and supervisory functions. Regions, instead, are responsible for territorial planning and programming duties. They prepare *Regional Waste Management Plans* (i.e., *Piani Regionali di Gestione dei Rifiuti*), which set specific targets, assign the location of treatment facilities, and define prevention and recovery strategies. Regions also authorize the construction and operation of treatment plants, as well as supervise operational activities. In many regions, however, part of the administrative functions is delegated to the provinces or other intermediate bodies. Finally, local governments (e.g., municipalities) have direct responsibility for the operational management of municipal waste. They organize collection, transportation, and, in some cases, treatment and disposal services, including by means of public or mixed companies. Municipalities must also ensure that minimum separate collection targets set at national and regional levels are met.

If on the one hand this multilevel articulation allows for an adaptation of management policies to territorial features, on the other hand it can generate problems of coordination and fragmentation of competencies, as highlighted by Agovino et al. (2023) and Camana et al. (2021). In particular, the effectiveness of management policies heavily depends on the institutional capacity of local authorities and the availability of financial and infrastructural resources. Recent studies highlight how the lack of homogeneity in Regional Plans and the absence of integrated planning between institutional levels contribute to the persistence of territorial imbalances in service quality and environmental performance (Chiades and Torrini, 2008). As far as operational responsibility is concerned, this is given to public or private entities through competitive bidding or direct awarding, in compliance with the principles of competition stipulated in the *Public Contract Code* (Italian Republic, 2023). The management service includes separate collection, transport, treatment, material or energy recovery and final disposal.

Another key role is played by the *Regulatory Authority for Energy Networks and the Environment* (ARERA, i.e., *Autorità di Regolazione per Energia Reti e Ambiente*), the independent Italian body in charged of regulating and controlling, among others, the urban waste management sector. Since 2018, following *Law No. 205 of December 27, 2017* (Italian Republic, 2017), ARERA has extended its competencies to this area, exercising its functions within the framework of the principles established by the founding *Law No. 481/1995* (Italian Republic, 1995). In the context of waste management, ARERA carries out several key activities. Firstly, ARERA prepares and updates the tariff method for determining service fees, based on the evaluation of efficient costs and the "polluter pays" principle. Secondly, the authority defines minimum quality standards for waste management services to ensure uniform levels throughout the country. It is also in charged of regulating the contractual and technical quality of the service, with the aim of ensuring a minimum and homogeneous level of quality for users. Thirdly, ARERA promotes transparency in the relationship between operators and users, establishing information obligations and ensuring that information on services is easily accessible and understandable. Lastly, the authority collects and analyzes data on the quality of waste management services in order to determine quality indicators and standards. This information is used to assess the need for regulatory interventions. As a result of these activities, ARERA seeks to ensure efficient, transparent and high-quality waste management services, contributing to the improvement of environmental performance and the protection of users across Italy.

Operationally, the Italian system is characterized by strong territorial heterogeneity. According to ISPRA (2023), northern regions achieve separate collection rates above 70%, supported by an established network of treatment plants. In contrast, southern Italy is characterized by lower levels of separate collection. As shown in Figure 6, in 2022 the percentage of separate collection exceeded 71% in the North, while the South stopped at 57.5%.



	Nord	Centro	Sud	Italia
2018	67,7	54,3	46,1	58,2
2019	69,6	57,8	50,6	61,3
2020	70,8	59,2	53,5	63,0
2021	71,0	60,4	55,8	64,0
2022	71,8	61,5	57,5	65,2

Figure 6: Trends in the percentage of separate collection of municipal waste, years 2018 - 2022. *The figure shows the disparities in separate collection rates among northern and southern Italian regions. Source: ISPRA (2023).*

Regarding landfilling, on the other hand, data in Figure 7 show that it is a phenomenon that does not affect only the South: some regions in the Center and North also show significant amounts of landfilling, indicating that the facility issue is transversal and not necessarily confined to a single geographic area.

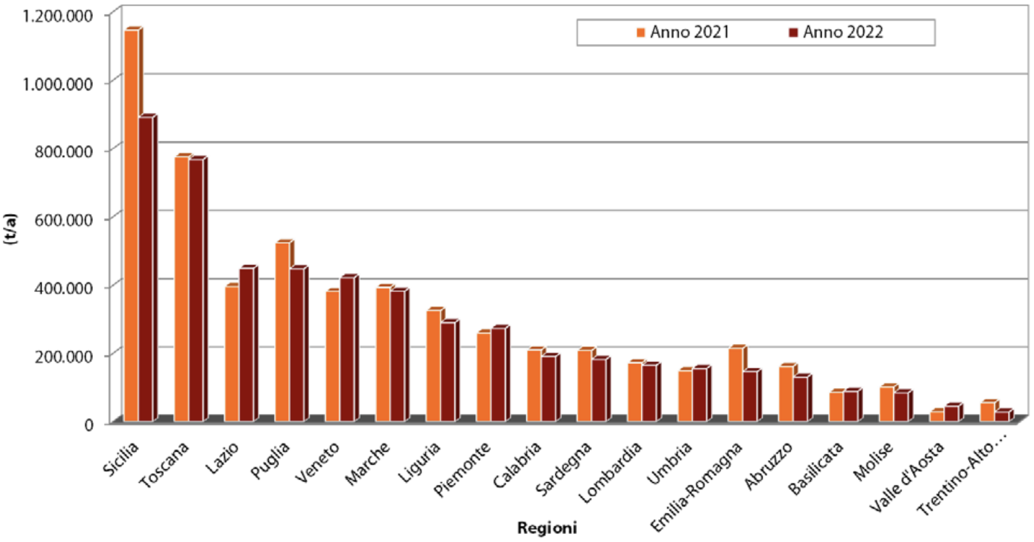


Figure 7: Municipal waste disposed in landfills, by region, years 2021 - 2022. *The figure illustrates that the landfilling issue is not confined to the South of Italy. Source: ISPRA (2023).*

Despite the fact that many regions still rely on landfilling, Figure 8 shows that, nationwide, the percentage of separate collection has steadily increased over time, from less than 20% in 2002 to more than 65% in 2022. This positive trend shows a significant effort in the direction of sustainability, although large territorial disparities in the contribution to achieving this result persist.

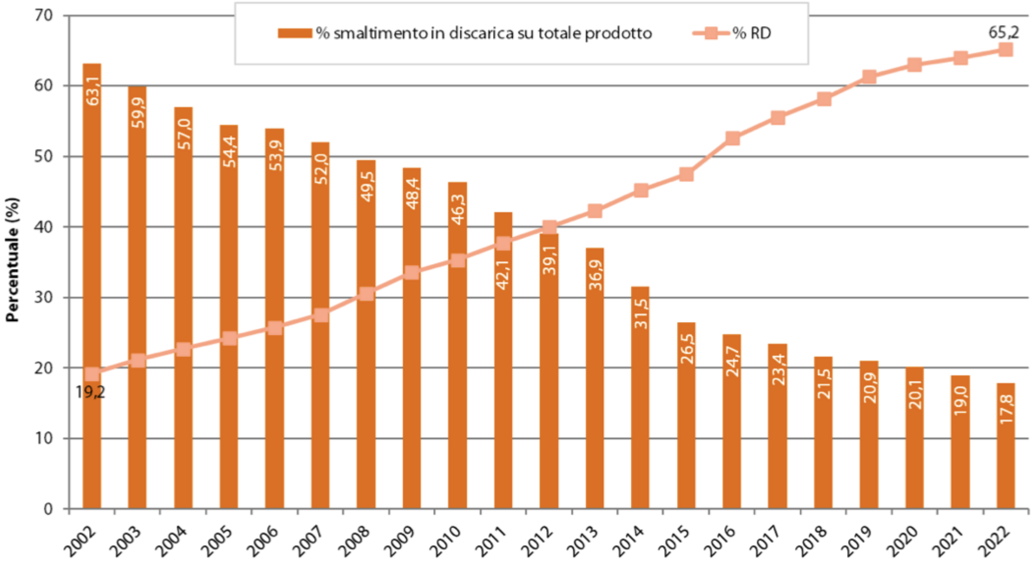


Figure 8: Trend in the percentage of landfill disposal versus the percentage of separate collection, years 2002 - 2022. *The figure shows the increase in the percentage of separate collection over the years. RD indicates Raccolta Differenziata, i.e., separate collection. Source: ISPRA (2023).*

In response to the various critical issues still present in Italy's waste management system, the *National Recovery and Resilience Plan* (NRRP, Italian Republic, 2021) has planned investments aimed at building new treatment facilities and strengthening recycling supply chains, allocating about 2.1 billion euros to improve waste management. Specifically, 1.5 billion euros were allocated to municipalities and local authorities in order to improve the mechanization of the separate collection of municipal waste and to encourage the modernization and construction of facilities. The remaining 600 million euros, on the other hand, were allocated to companies for the implementation of circular economy projects. In addition, new approaches, such as extended producer responsibility[4], are gaining a growing importance, with systems such as CONAI (*Consorzio Nazionale Imballaggi*, i.e., *National Packaging Consortium*) supervising the recycling of packaging on a national scale, ensuring compliance with recovery and recycling targets set at the European level.

Still, in order for such investments to produce lasting and significant results, it is essential to support them with a reinforcement of the administrative capacity of local authorities, better coordination between different institutional levels, and a careful assessment of the environmental and socio-economic impacts of the funded projects. Only through an integrated and systemic approach it will be possible to overcome territorial inequalities and make the Italian waste management system more efficient, equitable and consistent with the goals of the ecological transition.

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[4] In Italy, Extended Producer Responsibility is applied in several sectors, such as packaging, electronic waste, batteries, and end-of-life vehicles, through mandatory consortia or collective systems.

3.2 Disruption of the Waste Management Chain in Italy

In the last few years, the concept of supply chain disruptions has become central to the economic debate, especially following recent global events such as COVID-19 pandemic, energy crises, geopolitical conflicts, and international regulatory changes. Supply chain disruptions refer to significant, often sudden, disruptions that alter the normal flow of goods, services, or information along a supply chain, causing delays, inefficiencies, and increased costs (Ivanov and Dolgui, 2020). These disruptions can be due to exogenous causes (such as natural disasters, pandemics, or restrictive trade policies) or endogenous causes (such as organizational failures, infrastructural deficiencies, or technological vulnerabilities), and have spillover effects that propagate along the interconnected nodes of the chain.

As pointed out by Ivanov and Dolgui (2020), modern supply chains must be interpreted as interconnected and dynamic systems, characterized by integrated flows of goods, information, and resources. Their resilience can no longer be assessed only in terms of return to operational normality after a shock (i.e., recovery), but must also include long-term survival (i.e., viability). According to the authors, this requires structural reconfiguration of networks and integration of strategic planning. When applying this outlook to the waste sector, it is clear that a supply chain built on dependencies on a few external markets for processing or exporting materials cannot be considered sustainable or resilient. The lack of alternative routes, widespread plant capacity, and inter-institutional coordination makes the system vulnerable to regulatory or logistical shocks. Hence, even though the literature on supply chain disruptions has mainly focused on the manufacturing, food, health care and technology sectors, there is growing evidence that the waste management sector must also be considered an integral part of these dynamics. Waste management is not just a local service, but a real chain of complex and interdependent material flows, involving a plurality of public and private actors. It also depends on logistical infrastructures, international markets for recycled materials, environmental regulations, and treatment technologies. The multilevel and interconnected nature of this system makes it particularly vulnerable to external shocks and disruptions of strategic nodes in the chain (Ivanov et al., 2017).

In this context, the 2018 Chinese ban represented one of the most serious disruptions in the global recyclable waste supply chain, with widespread and long-lasting systemic effects. Until then, the system was based on a structural dependence on China as the main destination for plastic waste collected in high-income countries. The sudden closure of this channel caused a collapse of established logistics chains: flows were suddenly without a final destination, generating an unexpected accumulation of waste at ports, collection centers, and sorting facilities. This resulted not only in delays, congestion, and increased costs, but also in increasing pressure on domestic processing systems, which were often inadequate to handle the excess volumes. Furthermore, the attempt to relocate flows to new countries has led to the fragmentation of the supply chain, resulting in heterogeneous environmental standards, poor traceability, and frequent episodes of illicit trafficking or inappropriate disposal. From a systemic perspective, this situation has shown that recycling supply chains are vulnerable and not very adaptive to regulatory or trade shocks. The economically efficient approach has shown its limitations in the absence of local processing capacity or operational alternatives. Excessive dependence on a single global buyer has prevented exporting countries from reacting promptly, revealing the lack of diversification and resilience strategies. On the other hand, however, the crisis has also generated greater awareness of the need to relocate some plant capacity and invest in more circular solutions.

Nonetheless, despite the awareness of the need to take more sustainable actions, the *OECD Global Plastics Outlook* report (OECD, 2022b) shows that global plastic production will continue to grow. Figure 9 clearly illustrates this trend. Specifically, the share of secondary plastics[5] is expected to increase by 100% between 2020 and 2060, and the share of primary plastics[6] is expected to increase by about 175%. So, despite efforts, current policies are still not enough to counter the trend and new recycling chains will be needed.

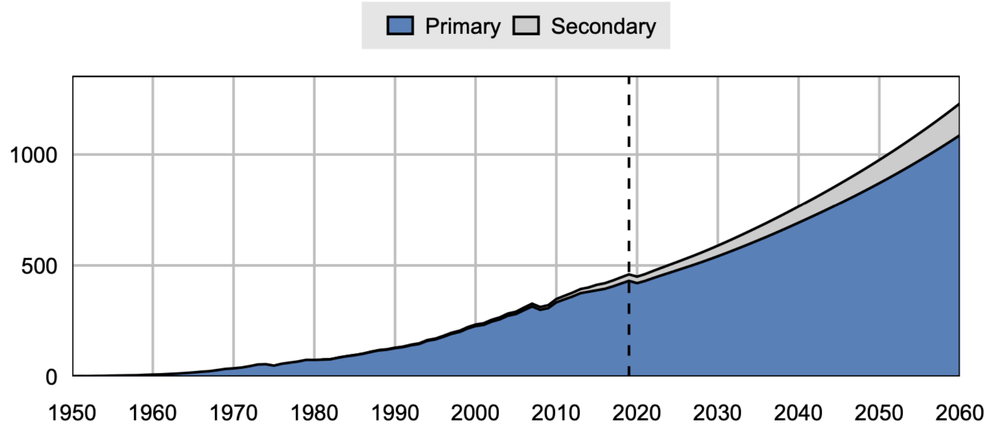

Figure 9: Primary and secondary plastics production in million tonnes (Mt), 1950-2060. *The figure shows the major increase in the global production of plastics between 2020 and 2060. The dashed line indicates year 2019. Source: OECD (2022b).*

In the Italian case, the Chinese ban has exposed the structural fragilities of a national waste supply chain still heavily dependent on outsourcing. Italy was heavily exporting fractions of plastic and special waste to third countries, partly for economic reasons, but also because of insufficient plant capacity. In some regions, in the absence of an alternative disposal and treatment plan, the ban has caused temporary interruption of the collection of some waste fractions, the need to store materials whilst waiting for their destination, and, in extreme cases, the risk of uncontrolled accumulations with potential health and environmental consequences (ARERA, 2020). Critical logistical issues have also reflected in increased difficulty in meeting timelines under service contracts and increased litigations between local authorities and waste operators. From a regulatory point of view, the need to domestically dispose of quantities previously handled abroad has led to delays in plant construction, authorization difficulties, and barriers due to institutional fragmentation. In many local realities, the lack of a clear and shared strategy on the location of plants has also generated social opposition (i.e., NIMBY - Not In My Back Yard - protests), hindering infrastructure development. The lack of evenly distributed plant capacity among Italian regions has also generated an imbalance in inter-regional

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[5] Secondary plastics refers to plastics obtained through the recycling of pre-existing plastic waste. This material is treated, sorted, and processed into new semi-processed products to be released back into production processes.

[6] Primary plastics refers to plastic produced directly from resources such as crude oil, natural gas or biomass. It is the new plastic material generated through industrial chemical processes and used for the first time in the production of goods.

waste flows. On the one hand, some regions, lacking adequate facilities, are forced to export waste, while on the other hand, others find themselves managing quantities in excess of their local needs. In Lombardy, for example, the presence of a large and articulated plant system has led to receiving significant volumes of waste from other regions, with consequences for the tariff system, the transparency of the supply chain, and the overall quality of the service (Regione Lombardia, 2022). Finally, the crisis has also had impacts on the demand for secondary raw materials[7]. The difficulty of placing some recyclable fractions, especially due to unstable international markets, has negatively affected the economic sustainability of recycling, making it more costly to maintain the required environmental standards.

As pointed out by Mazzanti and Zoboli (2009), in European countries, and to some extent in Italy, environmental policies introduced since the early 2000s have helped reduce the use of landfills, although nevertheless urban waste generation continues to grow with consumption. Overall, despite this progress on the recycling side, in economic terms in Italy the disruption of the waste supply chain triggered by the Chinese ban has led to significant effects on several levels. On the operational level, there has been an increase in transportation and disposal costs, delays in collection cycles, and increased pressure on facilities already at capacity limits. At the municipal level, budget issues were observed due to the need to adopt expensive solutions, such as transferring waste inter-regionally or abroad. At the employment level, the difficulties of recycling supply chains have contributed to a decline in investment and a loss of competitiveness for companies involved in circular economy sectors (OECD, 2024). Hence, waste chain disruption is not an isolated event, but the expression of a systemic vulnerability that requires a change of scenery. As suggested by Katsaliaki et al. (2022), supply chain resilience depends on the adaptability of infrastructures, institutional readiness to respond to shocks, and the ability to plan resilient and widespread solutions.

In light of all that has been said, it is essential to recognize waste management as part of the critical national infrastructures, itself subject to the same principles of protection and adaptability proper to production chains. So, among the essential steps Italy must take to transform the current vulnerability into an opportunity for modernization certainly are: (1) strengthening the planning and investment capacity of local governments, (2) promoting coordinated multilevel governance, (3) incentivizing technological innovation, and (4) ensuring greater plant self-sufficiency.

3.3 Fires at Waste Management Facilities in Italy

In recent years, the Italian waste management system has experienced an increasing number of fires at storage and treatment facilities. According to the *Parliamentary Commission of Inquiry into the Waste Cycle*, about 250 fires occurred at waste management and storage facilities between 2014 and 2017, with a 59% growth between 2016 and 2017 alone (Commissione Parlamentare d'Inchiesta sul Ciclo dei Rifiuti, 2021). These events raise serious environmental and health concerns and are an indi-

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[7] Secondary raw materials are materials obtained from the recovery and recycling of waste, which can be reused in production cycles in place of virgin raw materials. As such, they are resources resulting from waste treatment and valorization processes, which meet certain quality and safety requirements and stop being considered waste in accordance with European legislation on the *end of waste* concept (Article 6 of *Directive 2008/98/EC*, as amended by *Directive (EU) 2018/851*). Secondary raw materials are a key pillar of the circular economy, as they reduce natural resource use, environmental emissions, and disposal-related costs.

cator of structural vulnerability of the entire supply chain. Fires are not isolated phenomena. Several factors contributed to these events: excessive accumulation of waste at storage sites, lack of adequate facilities in some areas of the country, and tensions caused by the closure of foreign markets, as in the case of the Chinese ban. In many cases, the causes of the fires have been arson or negligence, but self-combustion hypotheses resulting from bad management of materials are also frequent. As recent studies show, similar phenomena have also occurred in other European countries, where facilities have been involved in arson or suspicious fires related to improper storage and weaknesses in waste traceability. In particular, in Sweden and Norway, there has been a frequent incidence of fires at waste storage facilities, often caused by spontaneous combustion or technical errors (Mikalsen et al., 2021). Similarly, in Poland, more than 750 fires occurred at illegal storage sites between 2017 and 2022, with significant impacts on soil, water, and public health (Kuta et al., 2023). Some similar incidents have also occurred in Spain, where the burning of an illegal tire dump resulted in population exposure to toxic substances, with significant health risks (Nadal et al., 2016).

As far as fires in Italy are concerned, a more in-depth analysis of the temporal dynamics of fires shows that the phenomenon intensifies at certain times of the year, particularly in the summer months, when rising temperatures can favor self-combustion phenomena. However, seasonality is not sufficient to explain the overall increase observed in recent years: correlation with structural variables in the system, such as plant capacity saturation and lack of rotation of stored materials, appears more meaningful for interpretation purposes. The nature of the facilities involved suggests that these are not just marginal or irregular facilities. Even facilities fully licensed and in compliance with current regulations have been affected by fire incidents, indicating potential critical issues in operational management, maintenance, and internal safety protocols. According to data in the *Parliamentary Commission* report, in about 20% of cases, the fire occurred in facilities that had already been reported for irregularities in incoming flows or overloading of materials.

An additional element of interest concerns the intentional or criminal nature of some fires. Investigations conducted by the judiciary and environmental authorities have documented episodes in which arson was a way of disposing of illegally accumulated or untraceable waste. These cases, albeit minor compared to the total, confirm the sector's vulnerability to criminal phenomena, especially in territories where controls are less thorough and the supply chain is less transparent. According to Legambiente (2022), the use of fire is among the most commonly used methods of illegal waste disposal, with peaks in Campania, Sicily, and Puglia. Another aspect to take into consideration is the reputational and economic impact that these fires generate on the waste treatment sector. Burning episodes, especially when they occur at authorized plants, reduce public confidence in the supply chain, fostering protests and opposition to the construction of new plants. This further hinders planning and expansion of treatment capacity, generating a vicious cycle that damages the overall resilience of the system. In addition, the costs associated with fire management, including firefighting, environmental rehabilitation, and facility restoration, often fall on local governments, worsening their financial burden.

In conclusion, the geographical and temporal distribution of fires at waste treatment sites suggests a strong connection with structural variables, such as plant capacity overload or management defects. However, the need to improve monitoring, strengthen system transparency, and invest in prevention remains crucial to structurally address this issue.

3.4 Literature Review: Facility Pressure, Fires, and Illicit Waste Management

The fires phenomenon in waste treatment and storage facilities has received increasing attention in recent studies, particularly in relation to two key variables: pressure on facilities and the fragility of tracking and control mechanisms. The existing literature offers relevant insights into how these dynamics may contribute to the increase in burning episodes, both accidental and criminal, within the supply chain. Several studies identify plant capacity overload as a major risk condition. According to Mikalsen et al. (2021), prolonged accumulation of materials in plants not designed to handle surpluses increases the likelihood of spontaneous combustion, particularly in the summer months. Lack of rotation of flows, combined with inadequate ventilation or the presence of unstable materials, can compromise operational safety even in formally authorized facilities. In Italy, the *Parliamentary Commission of Inquiry into the Waste Cycle* confirms that about 20% of fires occurred in plants already reported for material overloads or unusual flows. In parallel, the literature analyzes the role of illegal waste management practices as a triggering factor. According to Legambiente (2022), the use of fire is a common way to dispose of illegally accumulated or untracked waste, especially in areas where public control is weak and supply chain transparency is limited. INTERPOL (2020) showed an increase in illicit trafficking and arson related to mixed waste, exported illegally or accumulated in unauthorized facilities, especially after the 2018 Chinese ban. International studies support these findings. In Poland, Kuta et al. (2023) document more than 750 fires at illegal storage sites between 2017 and 2022, stressing the importance of regulated and tracked flow management. Whereas, Nadal et al. (2016) show, in the Spanish case, the health and environmental impacts of uncontrolled waste fires. A further strand of research explores the reputational and systemic implications of fires. Frequent episodes of burning, even in regular plants, undermine public trust in the legal supply chain and generate phenomena of NIMBY opposition to the opening of new plants, worsening plant scarcity and contributing to a vicious cycle of structural fragility. In this context, the literature has also highlighted how the fragmentation of Italy's multilevel system and weak local administrative capacity represent additional factors of inefficiency and vulnerability (Agovino et al., 2023; Camana et al., 2021). Finally, malfunctions in waste management systems are not necessarily local dysfunctions, but expressions of systemic issues. Ivanov et al. (2017), although referring to generic supply chains, point out how complex logistics networks are vulnerable to external shocks and operational discontinuities. Applying this perspective to the waste supply chain, events such as the Chinese import ban not only increase the volumes to be managed internally, but also help generate conditions that can facilitate phenomena such as arson.

Overall, despite the extensive literature on changes in waste trade routes and the systemic impact of the 2018 Chinese ban, there are still no studies that directly link such an exogenous shock to the increase in fires at waste management facilities. Available analyses have mostly focused on the commercial, environmental, and infrastructural effects of the crisis, or on individual aspects of illicit management, but there is a lack of quantitative analysis that tries to empirically measure a causal link between the post-2018 increase in plant load and the frequency of fires. This paper aims to fill this gap, offering an original contribution within a framework that is still being defined. In particular, this work adopts an empirical approach aimed at estimating the effect of plant pressure on the number of fires recorded at waste management sites in Italy. The objective is to test whether there is a statistically significant relationship between the intensification of treated waste, including following the 2018 Chinese ban, and the increase in fire episodes.

4 Empirical Analysis

The objective of this thesis is to investigate whether there is a significant relationship between intensifying pressure on waste management facilities in Italy and the frequency of waste fires. The theoretical starting hypothesis is that increased volumes of waste treated or stored may contribute to increased fire risk, for both technical and behavioral reasons. From an operational point of view, when a facility unexpectedly has to handle larger flows than usual, risks related to spontaneous combustion, deterioration of internal safety conditions, and difficulty in materials management can emerge. These critical issues can result in accidental events, especially during warmer months or in the absence of adequate fire safety protocols. From a behavioral perspective, however, it is assumed that excessive load, if not properly disposed of or tracked, may incentivize opportunistic or illegal forms of management, including arson as a means of reducing volumes or erasing traces of noncompliant flows. In particular, such practices may find greater applicability in territories where institutional control is weaker.

The basis of this hypothesis is the global exogenous shock caused by China's ban on the import of several categories of waste. For Italy, this has meant an immediate and significant reduction in waste exports, and thus a need to relocate internally a share of flows previously destined abroad. This shock has affected a system already marked by severe structural difficulties, leading to a sudden increase in the number of wastes to be treated domestically. If the hypothesis is correct, we would expect to observe an increase in fires in relation to increased pressure at the individual plant level.

4.1 Data and Construction of Variables

This section outlines in detail the process of collecting, selecting, and organizing the data used in the empirical analysis. The goal is to construct a panel dataset to explore the relationship between the pressure on the national waste management system and the number of fires recorded at storage, treatment, or disposal facilities.

The first part (4.1.1) explains the main information sources from which the data were obtained and the process followed to arrive at the creation of the final dataset. The second part (4.1.2), on the other hand, presents the variables constructed for the analysis, distinguishing between dependent, independent, and control variables and providing the main descriptive statistics.

4.1.1 Data Sources and Dataset Construction

To conduct the empirical analysis, an original dataset was constructed at the Italian municipal level by integrating information from various public and semi-structured sources. The data collected cover the period 2016-2022 and include both fires that occurred at waste management facilities and those that occurred elsewhere not related to waste, as well as the pressure on facilities in terms of volumes treated and available capacity. This section describes the sources used and the criteria adopted for the integration and construction of the final dataset, also explaining the sources of the control variables and their choice.

4.1.1.a Fire Data

To analyze the temporal and geographical distribution of waste management-related fires in Italy, an original dataset was constructed from different data sources. The goal was to collect data regarding all types of fires that occurred between 2016 and 2022 and then classify them between fires that occurred at waste treatment, storage, or disposal facilities or fires not related to waste management. Several subcategories were created within the two main types of fires.

The first source used is the georeferenced map *Incendi Impianti Rifiuti* (i.e., *Waste Plant Fires*), curated by Claudia Mannino, a deputy of the 17th Legislature of the Federation of the Italian Green Party, which collects reports of fires at waste management facilities based on local and national press articles. Each reported event is accompanied by date, geographic location, and type of facility involved. The categories considered are: *Waste facilities*; *Landfills*; *MBTs (Mechanical-Biological Treatments), recycling centers, MCCs (Municipal Collection Centers), platforms, and compactors*; *Composting plants*; *Other types of facilities*; *Incinerators*; and *Illegal areas.* The categories in the original map *STIR and SIR in Campania*[8] and *seized warehouses full of waste*[9] were excluded because they were not directly consistent with the classification under analysis.

Below is a list of definitions for each fire category in the map in order to clarify the nature of the data considered in the analysis. The category *waste facilities* refers to waste storage, which is the waste management operation of depositing waste in a site while awaiting its final destination. The category *landfills*, according to the establishment of *Legislative Decree No. 36 of January 13, 2003* (known as the *Landfill Decree*, Legislative Decree No. 36/2003, 2003), refers to an area intended for the disposal of waste by depositing it on the ground or underground. It also includes situations where waste is stored for a period of more than one year. Excluded from this definition, however, are facilities where waste is only dumped for subsequent transport to recovery, treatment, or disposal facilities, as well as temporary storage sites for up to three years if intended for recovery or treatment, or one year if intended for disposal. The category *MBTs, recycling centers, MCCs, platforms, and compactors* is a broad set that also includes fires involving waste transport trucks or dumpsters. MBT is a cold process consisting of two phases, mechanical and biological, applicable only to undifferentiated waste. During the mechanical phase, inorganic materials are separated, sorted, and sent for recycling at specialized plants. In the biological phase, on the other hand, the organic fraction is treated by anaerobic digestion or composting, producing biogas that can be used to generate electricity and heat. *Composting plants* transform the organic fraction of waste into compost. These facilities process both organic waste from municipal collection and waste obtained from the mechanical separation of mixed waste. The category of *incinerators* includes all industrial plants that dispose of waste by combustion, a process that allows the production of thermal or electrical energy. The category of *illegal areas* includes fires that occur at

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[8] STIR facilities (i.e., waste shredding and packaging plants) and SIR sites (i.e., sites of regional interest) were excluded from the analysis because they have different functional characteristics and purposes than the facilities under study. In particular, STIRs play an intermediate role in waste pretreatment, with limited waste permanence, while SIRs do not represent operational facilities for current waste management, but rather contaminated areas subject to remediation, the inclusion of which would have altered the consistency and homogeneity of the analyzed sample.

[9] Seized warehouses filled with waste were excluded from the analysis because they are sites already under judicial seizure and therefore under the control of the competent authorities. In such contexts, fires cannot be considered indicators either of increased pressure on the waste management system or of malicious phenomena related to illegal management, appearing rather as isolated events with different dynamics than active plants or illegal uncontrolled sites.

waste collection or storage sites that are not authorized by current regulations. Finally, the category of *other types of facilities* brings together all incidents of waste burning that do not fall into the previously defined categories. For the various categories, the following is the amount of data collected: 105 fires in *landfills*, 410 in *waste facilities*, 131 in *MBTs, recycling centers, MCCs, platforms, and compactors*, 13 in *composting plants*, 265 in *illegal areas*, 69 in *other types of facilities*, and 26 in *incinerators*.

To provide a broader comparison and context, a second dataset was created by extracting data from the Fire Department's intervention maps[10] for years 2014-2022. This source includes all fire-related interventions, regardless of the nature of the activity involved. The purpose of this methodological choice is to provide a baseline measure of the total number of fires that occurred in Italy during the period analyzed. The data have been classified into seven categories: *Wildfires and vegetation fires*, *Fires in homes and shops*, *Fires in industrial facilities*, *Fires in agricultural facilities*, *Vehicle fires*, *Fires in waste storage facilities and warehouses*, and *Other*. The division into these categories is used to distinguish the different contexts in which fires occurred, allowing for a clearer analysis and better identification of fires that are waste-related or not.

The different types of fires in the map are explained below to better understand what data were considered in the analysis. The *wildfires and vegetation fires* category includes all incidents reported on the Fire Department's maps that involve fires in forests, brush, Mediterranean scrub, hay bales, and general vegetated areas. The category *fires in homes and shops* includes all fires that occurred in villas, apartments, buildings, garages, small commercial activities, and stores. The category *fires in industrial facilities* includes all fires that have developed inside warehouses or structures with industrial use. Examples include furniture factories, fireworks plants, gas pipelines, construction sites, or food and textile industries. The category *fires in agricultural facilities* includes all fires in barns and agricultural storage facilities. The category *vehicle fires* includes all fires of automobiles, coaches, buses, trucks, and other vehicles. The category *fires in waste storage facilities and warehouses* collects all cases in which fires occurred in facilities such as warehouses, sheds, or silos containing waste or waste materials, including those at enterprises that specialize in handling and processing waste, such as plastics or other materials. Lastly, the *other* category includes all fires that do not fall into the categories listed above. According to the data collected, 425 fires occurred in vegetation and forested areas, 384 in private homes and stores, 206 in industrial facilities, 122 in agricultural facilities, 183 in warehouses or garbage deposits, 61 in other settings, and 233 were vehicle fires.

In order to build a single consistent and duplicate-free database, cleaning and doubles removal was carried out, after which 41 observations were dropped. At the end of the aggregation process, the resulting dataset includes 2,528 total observations, and for each observation there is information regarding the location of the fire, the municipality (and thus the province and region), the exact date, and the specific type. Finally, a further, broader classification was made, dividing all collected data into only two macro-categories: (1) *Waste fires*, i.e., fires related to the waste chain, and (2) *Non-waste fires*, i.e., all other categories unrelated to waste. Specifically, *waste fires* include the following above-mentioned categories: *illegal areas*; *composting plants*; *MBTs, recycling centers, MCCs, platforms, and compactors*; *landfills*; *waste facilities*; *other types of facilities*; *incinerators*; and *waste storage facilities and warehouses*. Conversely, *non-waste fires* include all the remaining categories.

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[10] Available at https://www.vigilfuoco.tv/mappe-interventi/ultimi-7gg.

In the end, the period of analysis considered for the final study was limited to the years 2016-2020 to ensure temporal compatibility with the other variables of interest and temporal consistency with the shock under consideration. In addition, the analytical focus was kept exclusively on the first macro-category. Hence, after reducing the time span and considering only waste fires, the dataset used in the empirical analysis contains 947 observations.

4.1.1.b Waste Facility Data

To analyze the pressure on the Italian plant system, an original dataset was constructed from data contained in the *Rapporti Rifiuti Urbani* (i.e., *Urban Waste Reports*) published by ISPRA for the years 2017-2023, in order to cover the observation period between 2016 and 2022. The annual reports contain detailed information on municipal waste treatment, storage, and disposal facilities, constituting one of the main official sources at national level.

The dataset was manually built by extracting and unifying data reported in different reports. Each observation corresponds to a plant that was active in a given year and is identified by the name of the municipality, the province, the region it belongs to, and the reference year. For each plant, information regarding authorized capacity, waste treated, and plant type was collected. Specifically, the variable representing the maximum authorized capacity indicates the maximum amount of waste that the plant is legally authorized to treat or dispose of during the year, in accordance with the environmental authorizations issued by the competent authorities. This value, expressed in tons or cubic meters depending on the type, represents the formal operating limit of the plant. Total waste treated, instead, measures the actual amount of waste handled by the plant in the reporting year, calculated at the end of December. The figure provides an estimate of the plant's pressure and level of utilization compared to the authorized capacity. Finally, each plant is classified based on its technical function according to the categories provided in the regulations and ISPRA classification. The main categories identified are: *Municipal waste landfills* (m^3), *Composting plants* (tons), *Anaerobic digestion plants*[11] (tons), *Integrated anaerobic/aerobic treatment plants*[12] (tons), *Mechanical treatment plants*[13] (tons), and *MBTs - Mechanical Biological Treatments* (tons).

The resulting dataset includes a total of 3,890 observations, covering waste treatment and disposal facilities operating in Italy between 2016 and 2022. The various categories have different numbers of observations within them. Specifically, there are 644 municipal waste landfills, whose capacity is expressed in cubic meters, 1,911 composting plants, 162 anaerobic digestion plants, 270 integrated anaerobic/aerobic treatment plants, 106 mechanical treatment plants, and 797 MBTs. For all categories except landfills, capacity and volumes treated are given in tons. For the purposes of the empirical analysis, it was necessary to apply a selection procedure for facilities at the municipal level in order to avoid methodological problems when calculating geographic distances between facilities and fires. To overcome this ambiguity and ensure stability in the geographical association, it was decided to keep

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[11] Plants that treat the organic fraction of waste in the absence of oxygen, generating biogas usable for energy production and a solid residue called *digestate*, which is sent for further treatment or disposal.

[12] Plants that combine an initial anaerobic phase, in which organic materials are degraded to produce biogas, with a subsequent aerobic phase aimed at stabilizing the residual material through oxygenation.

[13] Facilities that perform physical separation of municipal solid waste, distinguishing between dry and wet fractions through processes such as screening, shredding, and sorting, without biological intervention.

only one plant for each municipality, selecting the one with the highest authorized capacity, assuming that it is the main local disposal hub and, therefore, the most relevant for the purposes of the analysis. At the end of this selection, 1,976 observations remained. In addition, although data were initially collected for the entire 2016-2022 period, the analysis was limited to the years 2016-2020. This choice is motivated by the need to balance the pre- and post-Chinese ban periods, while maintaining consistent quality among all the data collected.

To complete the plant picture and take into account the possible impact of the Chinese ban on other waste flows as well, data on special waste plants were added to the dataset on municipal waste plants. Data on these plants were collected from the *Rapporti Rifiuti Speciali* (i.e., *Special Waste Reports*) published by ISPRA for the years 2016-2020, and integrated into the main database according to the same classification criteria. Three categories of special waste landfills, classified according to the type of waste treated, were considered in the integration process: (1) *Landfills for inert waste*, i.e., waste that does not undergo significant physical, chemical, or biological transformations, with a total of 749 facilities; (2) *Landfills for non-hazardous waste*, which are for the disposal of municipal solid waste or similar, with 762 total facilities; and (3) *Landfills for hazardous waste*, i.e., waste containing harmful substances that require specific management measures, with a total of 62 facilities.

The final integrated dataset includes 3,352 observations, of which 1,376 refer to special waste facilities. Given the presence of two types of landfills, i.e., for municipal waste and for special waste, in order to avoid duplication, overlaps due to the presence of mixed landfills, i.e., facilities that treat both municipal and special waste, were eliminated. In addition, in the case of multiple landfills present within the same municipality, only the one with the largest capacity was kept, following the same criterion adopted for other facilities. This approach is based on the assumption that larger landfills are more exposed to receiving extra flows or overloads, and therefore may be more vulnerable to situations of operational pressure. After cleaning, the final dataset used for the empirical analysis includes 2,841 observations, related to plants operating between 2016 and 2020, representative of the waste management system at the national level. Of these, 1,550 facilities treat municipal waste, while 1,291 are facilities for special waste.

4.1.1.c Control Variables Data

In addition to the main variables of interest, several control variables were included in the analysis, which are useful in capturing structural or territorial factors that may influence the incidence of fires at waste management facilities. In particular, an original measure of geographic isolation of facilities was constructed based on location information collected for each facility. The isolation variable was obtained by calculating, for each plant and for each year, the kilometric distance to the second closest plant in the country. Distances were calculated using the geographic coordinates of each plant. Thus, for each plant, the minimum distance from another plant in the same year was calculated, and this value was normalized to a range from 0 to 1 in order to obtain a continuous indicator of the degree of relative isolation. Including this variable in the controls allows for the fact that geographic isolation can affect the operating pressure of plants and, consequently, the risk of fire.

In addition, information was collected at the regional level regarding total waste generation, resident population, and exported quantities of waste. With regard to waste generation and export, these data were extracted separately for municipal waste and special waste, so that the two main flows could be analyzed separately. From these raw quantities, a derived variable was constructed. Specifically, a variable expressing the share of exported waste in the total produced was built. This was calculated by distinguishing between municipal and special waste, since the degree of openness to export may vary between the two categories. In the final dataset, this variable was not aggregated across categories but kept as separate indicators for municipal and special waste. This choice allows for a more accurate understanding of regional differences in waste management, helping to improve the accuracy of the results.

Overall, the inclusion of all these variables makes it possible to account for structural heterogeneity between regions that can indirectly influence the operational capacity burden of plants and, ultimately, the likelihood of critical events such as fires.

4.1.2 Main Variables Description

This section introduces the main variables used in the empirical analysis, distinguishing between dependent variable and key variable of interest. For each, the main descriptive statistics and, where relevant, some observations on their distribution, variability, and behavior over the period analyzed are given. The goal is to provide a clear overview of the explanatory characteristics of each variable and their potential interpretative implications within the model.

4.1.2.a Dependent Variable: Number of Fires

The dependent variable used in the analysis measures the number of fires that occurred at each waste management facility in a given year. Although the time frame covered in the empirical analysis is 2016-2020, the construction of this variable is the result of an aggregation process from a larger database, in which all fires recorded in Italy between 2016 and 2022 were collected and classified by type. From this initial dataset, a distinction was made between fires related to the waste chain (waste fires) and fires not related to waste management (non-waste fires), such as forest, industrial, or vehicle fires not related to plant activities. As shown in Table 1, in the 2016-2020 period, there are a total of 1,782 fires, of which 947 can be classified as waste fires, i.e., related to waste management facilities or activities.

Table 1: Number of Fires per Year, by Waste-Related vs Non-Waste-Related Typology

Year	Non-Waste Fires	Waste Fires	Total
2016	34	24	58
2017	132	144	276
2018	207	310	517
2019	203	289	492
2020	259	180	439
Total	835	947	1,782

Note: The table reports the number of fires recorded each year, distinguishing between those related to waste treatment facilities (e.g., landfills, TMB, platforms) and those unrelated to waste activities (e.g., wildfires, vehicle fires).

The regional distribution, illustrated in Table 2, shows marked territorial differences: the regions with the highest number of waste fires are Sicily (137), Campania (117), Lazio (101), and Lombardy (101). In contrast, some regions such as Valle d'Aosta, Trentino-Alto Adige, and Molise show an almost negligible presence of the phenomenon. These differences likely reflect heterogeneous factors such as plant equipment, pressure on storage sites, and the dynamics of illicit management at the local level.

Table 2: Geographical Distribution of Fires by Region and Waste-Related Typology

Region	**Non-Waste Fires**	**Waste Fires**	**Total**
Abruzzo	13	16	29
Basilicata	10	4	14
Calabria	26	44	70
Campania	37	117	154
Emilia-Romagna	120	42	162
Friuli-Venezia Giulia	27	12	39
Lazio	57	101	158
Liguria	37	29	66
Lombardia	76	101	177
Marche	64	14	78
Molise	3	4	7
Piemonte	39	68	107
Puglia	17	69	86
Sardegna	65	36	101
Sicilia	81	137	218
Toscana	57	99	156
Trentino-Alto Adige	2	1	3
Umbria	37	10	47
Valle d'Aosta	0	2	2
Veneto	67	41	108
Total	835	947	1,782

Note: The table reports the number of recorded fire events per Italian region, distinguishing between fires related to waste treatment facilities and those unrelated to waste activities.

Finally, Table 3 shows the distribution of waste fires according to the type of facility involved. The most affected category is *waste facilities*, with 309 fires or about 32%. This is followed by *illegal areas* with 257 fires and *MBTs, recycling centers, MCCs, platforms, and compactors* with 112 events. *Composting plants* and *incinerators*, on the other hand, account for a very marginal share. This distribution clearly shows that fires are not exclusively concentrated in illegal or non-compliant areas, but also significantly affect regular and authorized facilities, demonstrating how the phenomenon involves the entire waste management chain.

Table 3: Distribution of Waste Fires by Typology of Facility

Typology of Facility	**Frequency**	**Percent**	**Cumulative %**
Illegal Areas	257	27.14	27.14
Composting Plants	13	1.37	28.51
MBTs, recycling centers, MCCs, platforms, and compactors	112	11.83	40.34
Landfills	82	8.66	49.00
Waste Facilities	309	32.63	81.63
Other Types of Facilities	54	5.70	87.33
Incinerators	23	2.43	89.76
Waste Storage Facilities and Warehouses	97	10.24	100.00
Total	947	100.00	–

Note: The table includes only fires classified as waste-related.

Once fires unrelated to the waste chain were excluded, the data were aggregated at the plant-year level and merged with the dataset of municipal and special waste treatment plants, constructing a panel for the period 2016-2020. In this context, the variable representing the number of fires takes non-negative integer values, ranging from zero (no fires in the year) to 27 (maximum observed). As shown in Tables 4 and 5, the variable has a median of zero and over 81.6% of observations has value zero, confirming the zero-inflated nature of the variable. Moreover, the strong skewness (which amounts to 11.264) and the presence of outliers justify the use of nonlinear count models, particularly a two-stage hurdle model.

Table 4: Distribution of Facility-Year Observations by Fire Occurrence

Category	**Frequency**	**Percent**	**Cumulative %**
Facilities with at least one fire	521	18.34	18.34
Facilities with zero fires	2,320	81.66	100.00
Total	2,841	100.00	–

Note: Each row represents a facility-year observation. The same facility can appear multiple times if observed in multiple years.

Table 5: Detailed Descriptive Statistics of Number of Waste Fires

Statistic	**Value**
Observations	2,841
Mean	0.333
Standard deviation	1.213
Variance	1.472
Minimum	0
Maximum	27
1st percentile	0
5th percentile	0
10th percentile	0
25th percentile	0
50th percentile (Median)	0
75th percentile	0
90th percentile	1
95th percentile	2
99th percentile	4
Skewness	11.264
Kurtosis	193.659

Among plants that recorded at least one fire in a given year (521 observations, where the unit of analysis is plant-year), the average rises to 1.818 fires with a standard deviation of 2.310, and extreme values of up to 27 fires in the same year are observed, as shown in Table 6.

Table 6: Descriptive Statistics of Number of Waste Fires (When the Number of Fires Is > 0)

Variable	**Obs**	**Mean**	**Std. Dev.**	**Min**	**Max**
num_fires	521	1.818	2.310	1	27

However, Table 7 offers a different perspective because it aggregates information at the facility level, regardless of the year: indeed, it shows, for each facility, the maximum number of fires recorded in a single year between 2016 and 2020. According to this classification, 366 facilities (or 54.8%) never experienced fires during the entire observation period, while the remaining 302 experienced at least one incident. Of these, about 11% achieved at least two fires in the same year, and a very small proportion (0.75%) experienced an exceptionally high number of fires (up to 27), signaling possible recurrent critical situations.

Table 7: Distribution of Facilities by Their Maximum Annual Number of Fires (Across All Years)

Max. Fires Observed	Frequency	Percent	Cumulative %
0	366	54.79	54.79
1	185	27.69	82.49
2	72	10.78	93.26
3	17	2.54	95.81
4	9	1.35	97.16
5	10	1.50	98.65
7	3	0.45	99.10
9	1	0.15	99.25
11	1	0.15	99.40
12	1	0.15	99.55
13	1	0.15	99.70
24	1	0.15	99.85
27	1	0.15	100.00
Total	668	100.00	–

Note: The variable records the maximum number of fires that each facility experienced in any single year across the observation period. Facilities are counted once, and the year in which the maximum occurred is not retained.

From a time perspective, Table 8 confirms the existence of a localized shock around 2018: the number of waste fires increases from 24 in 2016 to 310 in 2018, and then gradually decreases until 2020. This trend, consistent with the introduction of the Chinese ban on waste imports, suggests a pressure and congestion effect on the system in the period immediately following the shock.

Table 8: Average Waste Fires per Waste Facility by Year

Year	Total Waste Fires	Number of Facilities	Fires per Facility
2016	24	581	0.041
2017	144	581	0.248
2018	310	559	0.555
2019	289	563	0.513
2020	180	557	0.323

Also, Figure 10 shows data for the years following the analysis period (i.e., 2021-2022) and is used for illustrative purposes to show that fire levels have gradually readjusted, returning to values similar to those in 2016. This behavior reinforces the hypothesis of a transitory but significant impact, triggered by the shock and subsequently absorbed by the system.

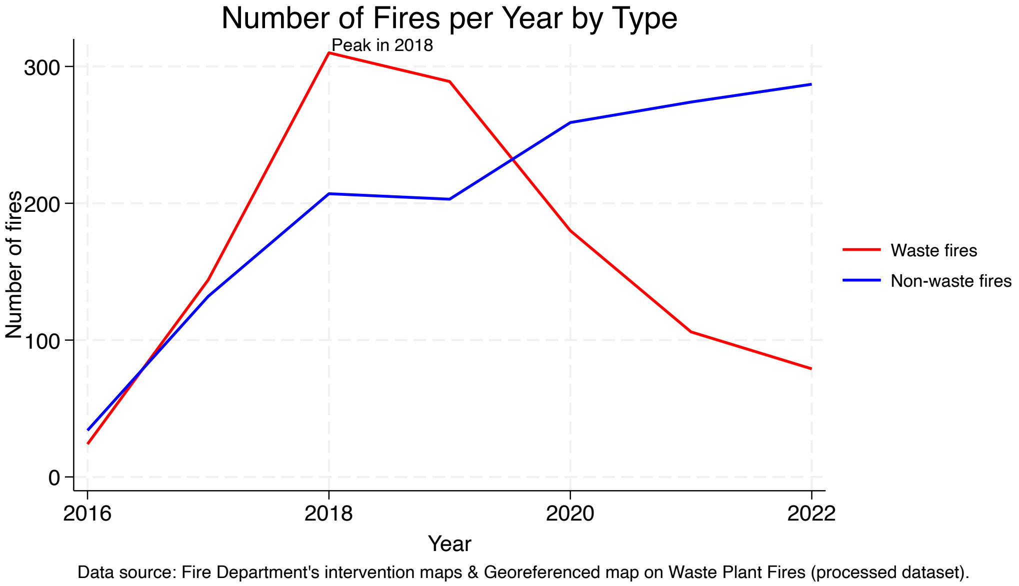


Figure 10: Trend in the total number of waste and non-waste fires, years 2016–2022. *The figure shows the annual evolution of recorded fires, distinguishing between waste-related and non-waste-related events. Waste-related fires increased sharply until 2018, reaching a peak, and then declined steadily. In contrast, non-waste fires continued to increase after 2018, surpassing waste-related fires in 2020. This increase is likely due to a spike in forest and vegetation fires, many of them arson-related or exacerbated by the extreme heat events that hit Italy in those years. Source: Fire Department intervention maps & Georeferenced map on Waste Plant Fires (processed dataset).*

4.1.2.b Main Explanatory Variable: Total Waste Treated

The main independent variable used in the analysis is the natural logarithm of the total amount of waste treated by each facility in a given year. The original data reflect the actual annual volume handled by each plant as reported at the end of the year. The logarithmic transformation was adopted to reduce the high skewness of the distribution and contain the impact of extreme values, ensuring more stability in the estimation of coefficients. As shown in Table 9, the distribution of treated volumes shows a strong skew to the right, with a mean of over 173,000 tons, but a significantly lower median (20,322 tons), confirming the presence of many facilities that treat little waste and a few facilities that treat a great amount of waste. The shape statistics also confirm a highly skewed distribution, with a skewness of 5.99 and a very high kurtosis (47.76), justifying the choice of transforming the variable into logarithms to normalize the distribution and reduce sensitivity to outliers.

Table 9: Summary Statistics of Total Waste Treated (in Tons)

Percentile	Value	Statistic	Value
1%	7	Mean	173,276.5
5%	75	Std. Dev.	543,096.5
10%	293	Variance	2.95×10^{11}
25%	2,323	Skewness	5.99
50%	20,322	Kurtosis	47.76
75%	78,841		
90%	346,601		
95%	933,212		
99%	2,854,595		

Note: This table reports distributional statistics for the total amount of waste treated across all facility-year observations, measured in tonnes. The distribution is highly right-skewed.

As shown in Table 10, the distribution of the logarithm of total waste treated shows an average of 9.49, with a 1st percentile at 1.95 and a 99th percentile at 14.86, confirming the strong heterogeneity in the volumes handled by facilities.

Table 10: Summary Statistics of the Logarithm of Total Waste Treated

Percentile	Value	Statistic	Value
1%	1.95	Mean	9.49
5%	4.32	Std. Dev.	2.77
10%	5.68	Variance	7.65
25%	7.75	Skewness	−0.52
50%	9.92	Kurtosis	3.16
75%	11.28		
90%	12.76		
95%	13.75		
99%	14.86		

Note: This table shows the distribution of the log-transformed total waste treated. Log transformation significantly reduces skewness and kurtosis, resulting in a more symmetric distribution.

Figure 11, moreover, shows a significant concentration of plants with log values between 8 and 11, which correspond, in real terms, to volumes handled between about 3,000 and 60,000 tons per year. At the upper end of the distribution, instead, are plants that treat more than 100,000 tons per year, with peaks exceeding 2 million tons. These large facilities, although numerically limited, represent real hubs in the supply chain, potentially more exposed to congestion or operational overload conditions.

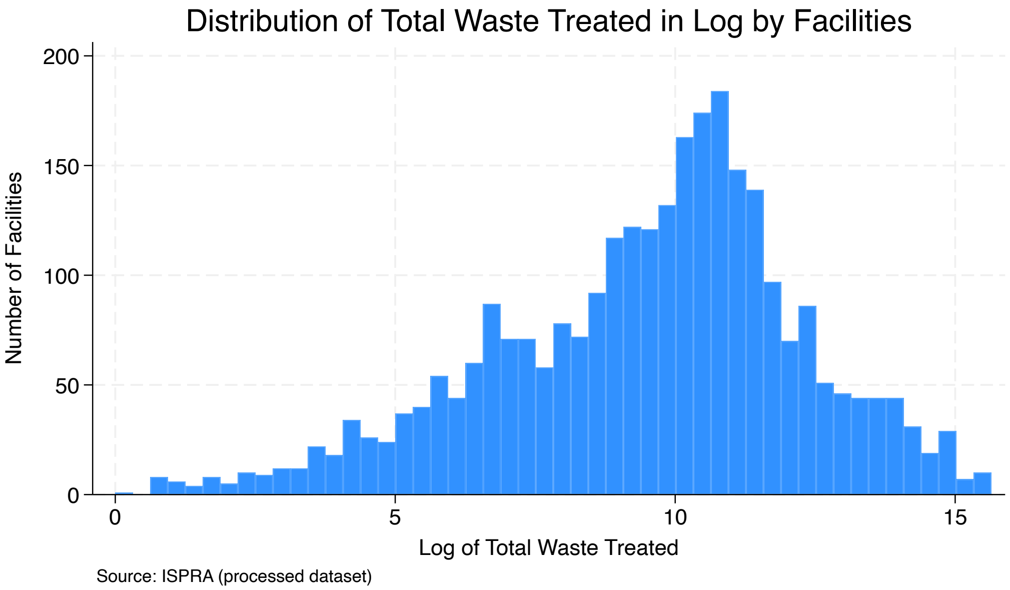


Figure 11: Distribution of total waste treated (log scale), by facility. *The figure illustrates the distribution of the total amount of waste treated across facilities, expressed in logarithmic scale. The distribution is right-skewed, with a high concentration of facilities processing moderate waste volumes (around the mean value of 9.5) and a long right tail indicating the presence of a few large-scale plants with very high treatment capacities. The 1st and 99th percentiles (1.95 and 14.86 respectively) highlight the strong heterogeneity in operational scale. This variability likely reflects structural differences across facilities in terms of type, technological endowment, and territorial function. Source: ISPRA (processed dataset).*

This interpretation is reinforced by the descriptive statistics disaggregated by plant type, shown in Table 11. The data highlight substantial differences between categories: municipal waste landfills handle an average of more than 830,000 tons per year, while composting plants process an average of only 14,000 tons. Other operationally intensive facilities include MBTs, mechanical treatment plants and integrated facilities, which also show high average volumes. This suggests that the technical function of the plant plays a crucial role in determining the level of operating pressure it is subject to.

Table 11: Summary Statistics of Total Waste Treated by Facility Type (in tons)

Facility Type	**Obs**	**Mean**	**Std. Dev.**	**Min**	**Max**
Municipal waste landfills	140	836,388	951,757	4,927	5,236,137
Landfills for inert waste	616	21,765	68,319	1	774,102
Landfills for non-hazardous waste	635	477,263	923,573	64	6,230,819
Landfills for hazardous waste	40	162,381	214,507	2	1,101,710
Composting plants	872	14,013	20,519	2	124,968
Anaerobic digestion plants	90	39,535	59,320	3	273,649
Integrated anaerobic/aerobic treatment plants	112	66,984	108,053	1,412	674,394
Mechanical treatment plants	29	85,060	104,155	12,612	589,564
MBTs – Mechanical Biological Treatments	307	86,233	82,607	1,251	835,974

Note: This table reports descriptive statistics for total waste volumes treated at each type of facility.

Table 12 also shows that only 11.05% of the facilities can be classified as "large", meaning they handle more than 300,000 tons per year. Although numerically small, these facilities handle a large share of the total volume of waste, and may therefore be more vulnerable to systemic risks in the event of logistical stress or exceptional loads.

Table 12: Distribution of Facilities by Threshold of Treated Waste Amount (300,000 tons)

Facility Type	**Frequency**	**Percent**	**Cumulative %**
Not a large facility	2,527	88.95%	88.95%
Large facility	314	11.05%	100.00%
Total	2,841	100.00%	–

Note: A facility is classified as "large" if it treated more than 300,000 tons of waste in a certain year. This classification captures differences in the amount of waste actually processed, not the facility's structural capacity.

Finally, Table 13 distinguishes plants according to the type of waste treated. Plants handling special waste account for about 45% of the total, but treat on average more than 250,000 tons per year, more than twice as much as plants handling municipal waste (about 109,000 tons).

Table 13: Distribution of Waste Treated by Facility Based on the Type of Waste Processed

Facility Waste Type	**Obs.**	**Percent**	**Mean**	**Std. Dev.**	**Min**	**Max**
Special Waste	1,291	45.44%	250,166	688,021	1	6,230,819
Municipal Waste	1,550	54.56%	109,235	370,845	2	5,236,137
Total	2,841	100.00%	–	–	–	–

Note: Facilities are classified based on the type of waste they treat (i.e., municipal or special waste). The table reports the number and share of facilities, as well as summary statistics for the total amount of waste treated (in tons).

From a temporal perspective, the average waste treated per plant shows a slightly increasing trend between 2016 and 2019, and a substantial stability in the following year, as shown in Figure 12. This trend is consistent with the hypothesis of an exogenous shock induced by China's ban of waste imports in 2018. In response to the foreign market closure, it is plausible that a significant portion of previously exported waste was redirected to Italian plants, generating a temporary increase in pressure on the domestic system.

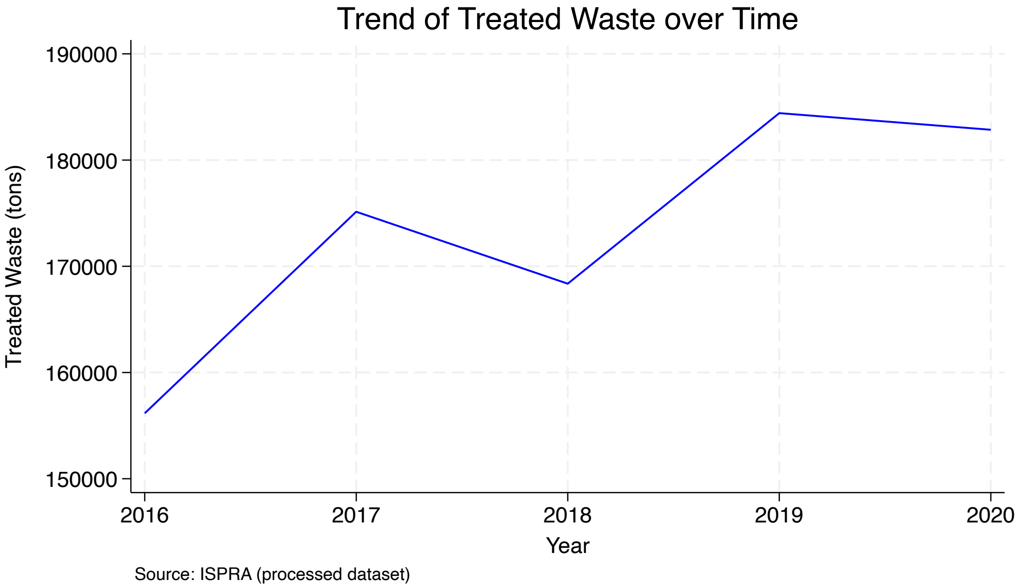
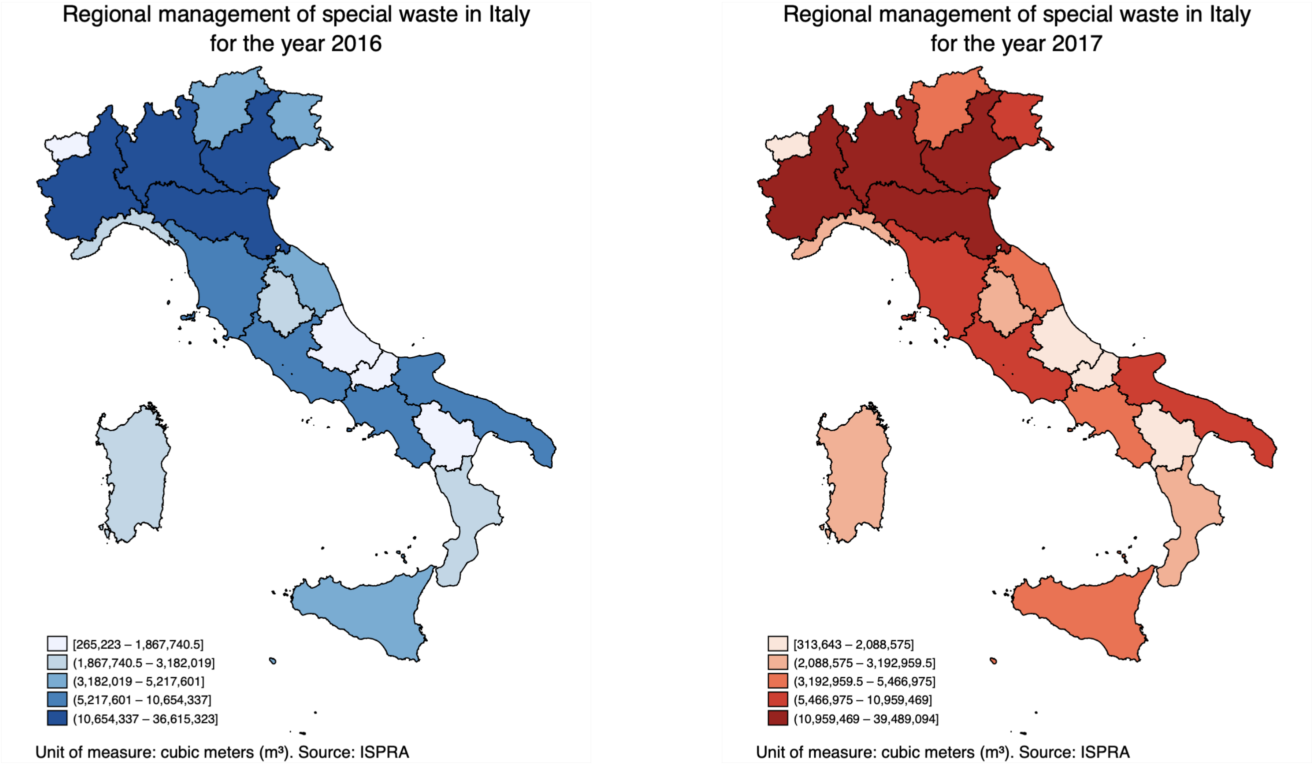


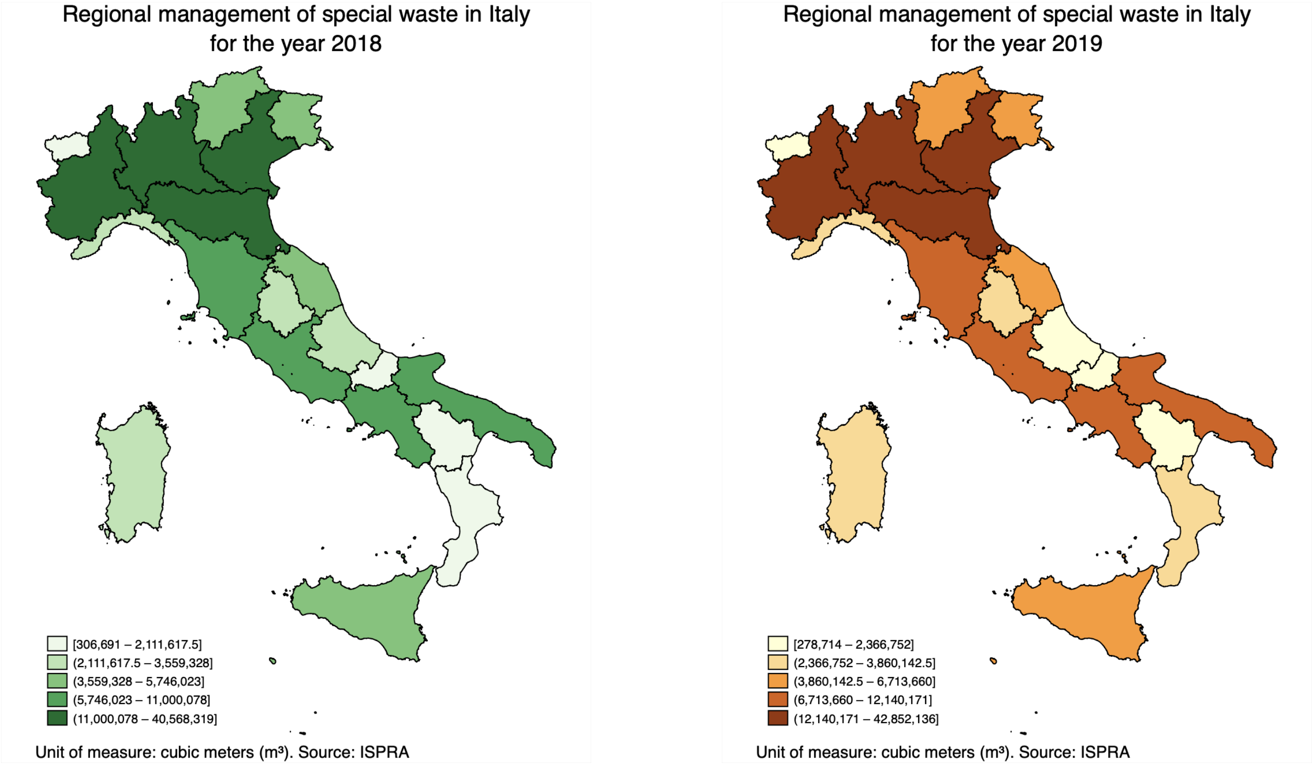
Figure 12: Trend in the Total Amount of Waste Treated, Years 2016–2020. *The figure illustrates a moderate upward trajectory in the volume of waste treated across Italian facilities between 2016 and 2019, followed by a phase of relative stabilization over the subsequent year. This pattern may reflect the consequences of China's 2018 import ban on foreign waste, which likely redirected a substantial share of previously exported materials back into the domestic system. Source: ISPRA (processed dataset).*

To better understand the geographical distribution of treated waste loads, a series of regional maps were made showing the management of special waste for each year from 2016 to 2020, as shown in Figure 13. The focus of the maps is on special waste because the fraction affected by the Chinese ban mainly concerned that category, along with plastic waste, for which, however, no separate breakdown is available in official data. The maps show a strong geographic disparity: regions such as Lombardy, Emilia-Romagna, Veneto, and Piedmont are systematically among the most affected in terms of volumes treated, suggesting that plant pressure is far from being homogeneous across the country.



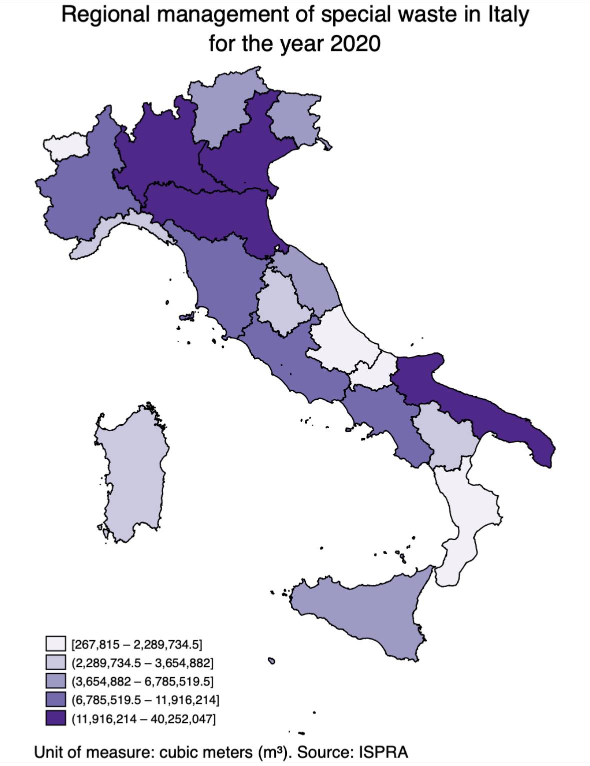
(a) 2016

(b) 2017



(c) 2018

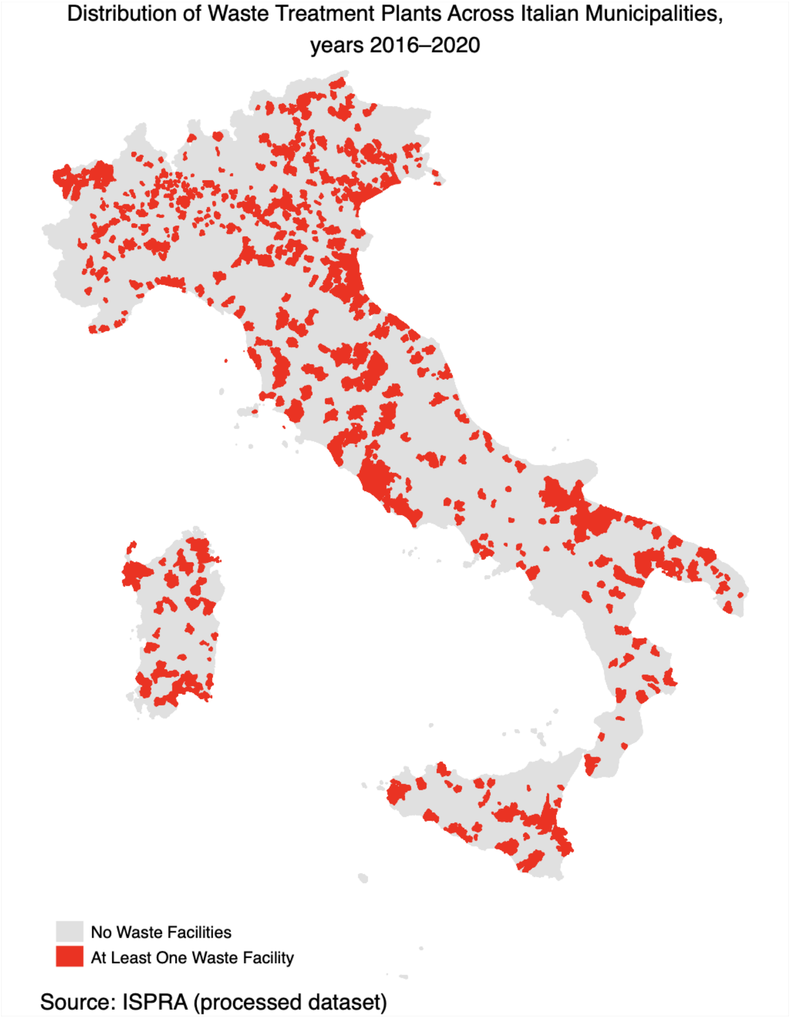
(d) 2019



(e) 2020

Figure 13: *Regional distribution of special waste treated in Italy, 2016–2020. The maps show volumes treated per region in cubic meters, grouped by quantile classes. Source: ISPRA (processed dataset).*

This pattern is further confirmed by the distribution map of all treatment plants in Italian municipalities (Figure 14), which shows a higher concentration in the North. In contrast, many areas in the Center and South show a sparer plant coverage, suggesting not only a different treatment capacity, but also a possible greater vulnerability in case of logistical stress.


Distribution of Waste Treatment Plants Across Italian Municipalities, years 2016–2020

Source: ISPRA (processed dataset)

Figure 14: Distribution of Waste Treatment Facilities Across Italian Municipalities, Years 2016–2020. *The figure shows the geographical distribution of waste treatment plants across Italy at the municipal level. Municipalities highlighted in red host at least one waste facility, while those in grey do not. The map reveals a widespread presence of treatment infrastructure, with a notable concentration in northern regions. Source: ISPRA (processed dataset).*

4.2 Empirical Strategy and Methodology of Analysis

The analysis has been conducted by implementing an empirical design involving two distinct phases. The first one consists of estimating a simple regression of the total amount of waste treated on a post-ban variable in order to test whether the regulatory shock has indeed generated a structural increase in pressure on the Italian plant system. The second part of the analysis, on the other hand, focuses precisely on the causal relationship between increased pressure in terms of treated waste and increased fire risk in Italy, and adopts a hurdle model, which allows to decompose the process generating fires into two separate components. On the one hand, the extensive stage, which estimates the probability that a facility will record at least one fire (modeled by a logit regression); on the other, the intensive stage, which analyzes the expected frequency of fires conditional on their occurrence (modeled by a negative binomial regression).

The reasons that justify the adoption of a hurdle model lie in the nature of the dependent variable. The number of fires shows a highly skewed distribution: about 81% of the observations take zero value, while the remaining ones show a strong overdispersion. This pattern cannot be attributed to simple stochastic variability, but most likely reflects a structural distinction between two pools of facilities. On the one hand, facilities that due to operational characteristics, location, or management conditions do not record fires during the entire observation period, and on the other hand, more exposed or vulnerable facilities that report even repeated events. As previously shown in Table 7, more than half of the facilities (54.8%) never experienced any fires between 2016 and 2020, while about 11% experienced at least two fires in the same year, and a small proportion experienced exceptionally high levels (up to 27 fires). This pattern suggests that the probability that a facility will record at least one fire and the number of observed events, once they have occurred, respond to different determinants. For this reason, a single-structure model is methodologically unsuitable to capture such heterogeneity. Some facilities may be in isolated, well-attended areas, others in settings with high incidence of illicit activity or critical operational pressures: the presence of zeros is not just a technical matter, but a demonstration of an underlying dual dynamic, requiring a two-stage modeling. Thus, this two-stage model more consistently reflects the causal structure of the phenomenon, distinguishing between the occurrence and intensity of events, and overcomes the constraints imposed by single-structure models. In addition, this approach is particularly suitable for dealing with count, overdispersed dependent variables with a high presence of zeros, as in the case of the number of fires, for which the observed distribution is characterized by a high incidence of zeros and a variance significantly above the mean.

4.2.1 Analysis of the Impact of the Chinese Ban on Italian Plant Pressure

The first part of the empirical analysis aims at assessing whether the Chinese waste import ban has had a direct and measurable impact on the pressure faced by Italian waste treatment plants. Specifically, it seeks to test whether, starting in 2018, a systematic increase in the amount of total waste treated at the plant level is observed. This step is a necessary condition for the validity of the two-phase strategy: in the presence of an actual pressure on the domestic waste management system, it is plausible to investigate, in the next stage, a potential causal link between this pressure and increased fire risk.

Formally, the estimated model is a linear regression for panel data, where the dependent variable is the amount of waste treated by each plant in each year. The key variable, on the other hand, is a *post* dummy, which takes value 1 for years after the ban takes effect (2018-2020) and 0 otherwise. The estimated equation is then as follows:

$$twt_{it} = \beta_0 + \beta_1 \cdot post_t + \beta_2 \cdot X_{it} + \delta_t + \mu_r + \lambda_s + \varepsilon_{it}$$

where twt_{it} is the total amount of waste treated at facility i in year t; $post_t$ is the treatment variable (post-ban), equal to 1 for years from 2018 onward, and 0 otherwise; X_{it} is a vector of control variables including the ratio between exported and produced waste in the region - to capture territorial exposure to the ban based on export dependency - and the density of facilities in the region; δ_t are year fixed effects, which control for macroeconomic shocks, national regulatory changes, and trends common to all plants; μ_r are regional fixed effects, to capture structural heterogeneity between territories; λ_s are plant type fixed effects, which control for different technological and operational characteristics among plant classes; and ε_{it} is the error term.

The identifying hypothesis is that, in the absence of the regulatory intervention, the trajectory of treated waste volumes would have tended to remain stable or influenced only by common trends. Any significant increase in the dependent variable in the post-ban period can then be interpreted as a plausible effect of the exogenous shock. It is important to emphasize that this phase does not aim to directly estimate the effect of the ban on the number of fires, but rather to empirically validate the central assumption that will guide the second part of the analysis, i.e., that the Chinese blockade actually resulted in an increase in operational pressure on Italian plants, measurable through a change in the amount of waste treated.

It is, however, worth pointing out a potential interpretive limitation of the first phase. The effect of the ban on the quantity processed could be mitigated by the presence of noise in the dependent variable due to its aggregate nature, which also includes waste not directly affected by the ban. In addition, since 2018, Turkey has gradually assumed a replacement role as the main destination for European waste exports, reducing the net impact of the Chinese outage. These two factors contribute to limiting the statistical significance of the estimated effect, though without invalidating its logical consistency. A more in-depth discussion of these issues are developed while showing the results.

4.2.1.a Results of the Analysis of the Impact of the Chinese Ban on Italian Plant Pressure

The first part of the empirical analysis aims to test whether the 2018 Chinese ban actually produced an increase in pressure on Italian plants, as measured by the total amount of waste treated. As shown in Table 14, however, the coefficient associated with the *post* variable, while positive, is not statistically significant ($p = 0.160$). This indicates that statistically it cannot be said with sufficient confidence that the volume of waste treated increased systematically in the period after the ban came into effect.

Table 14: Random-Effects GLS Regression with Clustered Standard Errors

Variable	**Coefficient**	**Std. Err.**	**z**	**p-value**
Post	32,614.49	23,193.07	1.41	0.160
Ratio_export	-2,337,584	1,736,273	-1.35	0.178
Plant_density	1,895,584	2,211,776	0.86	0.391
R-squared (within)		0.0253		
R-squared (between)		0.2764		
R-squared (overall)		0.2273		
Wald χ^2(33)		129.11 (p = 0.000)		

Note: The model includes fixed effects for year, facility type, and region (not reported for brevity). Standard errors are clustered at the facility level (668 clusters). The dependent variable is *totalwastetreated*.

However, the absence of statistical significance does not necessarily imply that the ban had no effect on the Italian plant system. On the contrary, there are plausible elements that explain why the effect may not emerge clearly from the estimation. First, the dependent variable used at this stage is an aggregate measure, including a variety of waste types, not all equally affected by the Chinese ban. Because the ban specifically affected certain categories of waste (particularly plastic and special waste), the inclusion of fractions not subject to the ban in the aggregate data also introduces a systematic component of statistical noise. In other words, due to the inability to find more disaggregated data, the effect of interest is drowned within a broader variability that reflects dynamics independent from the regulatory treatment. Second, it is necessary to consider that the Chinese ban has not resulted in a simultaneous and complete withdrawal of international demand for treatment, but has generated a recomposition of global export flows. In particular, since 2018, other countries, including mainly Turkey, have gradually replaced China as the main destination for European waste. Italy itself has significantly increased exports to these new trading partners, thereby reducing the amount of waste that, in the absence of alternatives, would have flowed entirely into the national system. While this phenomenon of trade substitution does not eliminate the ban effect, it does attenuate its empirical visibility, especially when working with aggregate data that do not allow to distinguish between flows that remain domestic and flows that are redirected elsewhere.

The combination of these two dynamics makes it more difficult to identify a statistically robust effect, even in the presence of a theoretically robust causal effect. For this reason, the first phase should be interpreted with caution: the results do not allow the claim that the ban led to a statistically significant increase in plant pressure, but neither do they deny the existence of an effect. Rather, they suggest that the observable measure of the phenomenon is blurred by information limitations and simultaneous shocks of an exogenous nature, which complicate the sharp identification of the impact. In a counterfactual scenario free from these distorting elements, or in the presence of more granular data disaggregated by waste type, it is plausible to assume that the effect of the ban on plant pressure would have emerged more clearly and significantly.

4.2.2 Analysis of the Relationship between Plant Pressure and Waste Fire Incidence in Italy

The second part of the empirical analysis investigates the relationship between plant pressure and the incidence of waste fires in Italy, while accounting for the specific distributional characteristics of the dependent variable. To do so, a hurdle model is adopted, which allows the two processes generating the large amount of zeros in the dependent variable to be treated separately: (1) the mechanism that determines whether a fire occurs at least once (extensive component), and (2) the mechanism that, conditional on its occurrence, determines how many fires take place (intensive component). Indeed, in the setting analyzed by this thesis, a significant proportion of zeros in the number of fires is structural, i.e., reflects a systematic condition rather than a random realization of the same generative process. Thus, this approach more accurately reflects the causal structure of the phenomenon analyzed by explicitly distinguishing the occurrence of the event from its intensity.

As shown by several correlation measures (Table 15), the link between the number of fires and the total amount of waste treated appears positive but nonlinear.

Table 15: Correlation Coefficients Between Number of Fires and Total Waste Treated

Method	**Coefficient**	**p-value**
Pearson's correlation	0.0526	–
Spearman's rho	0.1813	0.0000
Kendall's tau-b	0.1449	0.0000

Note: The table reports different correlation coefficients between the number of fires per facility and the total amount of waste treated. The p-values for Spearman's and Kendall's tests reject the null hypothesis of independence at the 1% level.

In particular, Pearson's coefficient shows a very weak linear relationship, while the nonparametric Spearman's ($\rho = 0.1813$) and Kendall's τ-b (0.1449) coefficients indicate a positive monotonic but nonlinear relationship that is statistically significant in both cases. This means that as the amount treated increases, the probability or intensity of fire also tends to increase, but not proportionally or consistently. Specifically, the shape of the relationship suggests the presence of jumps or discontinuities, which make nonlinear models more suitable. These evidences, combined with the presence of overdispersion and a very high fraction of zeros (more than 80%), make linear models inadequate and justify the adoption of nonlinear count models, specifically fitted for discrete and skewed distributions. For this reason, the second phase relies on the hurdle model, i.e., a kind of model that belongs to the theoretical framework of count models specifically suited for discrete and overdispersed data. Before going into the details of its implementation, it is useful to introduce the theoretical framework justifying its use.

Count models are designed to analyze variables that represent counts of integer, nonnegative events, as in the case of the number of fires recorded annually for each facility. In such contexts, the use of linear models such as OLS is inappropriate because it violates the assumptions of continuous, symmetric, and homoschedastic error distribution. The first standard model for count data is the Poisson regression, which assumes that the mean and variance of the number of events coincide. However, when the variance systematically exceeds the mean, that is, if there is overdispersion, as is the case in the data under consideration, the Poisson model produces inefficient estimates and underestimates the standard error. To overcome this limitation, the negative binomial model is used for the intensive component of the hurdle model. Indeed, the negative binomial is a generalization of the Poisson model and introduces an additional dispersion parameter that allows the variance to be greater than the mean. However, before going into detail on the model used for the intensive component, the specification of the extensive stage will be discussed.

The extensive component of the hurdle model estimates the probability that the event of interest (i.e., the occurrence of at least one fire) will occur. The dependent variable therefore assumes a dichotomous structure, equal to 1 if the observed unit records at least one event in the time interval under consideration, and 0 otherwise:

$$y_{it}^{*} = \begin{cases} 1 & \text{if } y_{it} > 0 \\ 0 & \text{if } y_{it} = 0 \end{cases}$$

The conditional probability of occurrence is modeled through a logistic function, according to the following formulation:

$$\Pr(y^*_{it} = 1) = \frac{\exp(\alpha_0 + X_{it}\alpha + \delta_t)}{1 + \exp(\alpha_0 + X_{it}\alpha + \delta_t)}$$

where y^*_{it} is the binary outcome variable indicating the presence or absence of the event for unit i at time t; X_{it} is the vector of observed explanatory covariates; α_k are the parameters to be estimated; and δ_t represents a set of year fixed effects, capturing time-specific shocks common to all units. This formulation allows for a flexible estimation of the probability that the observed unit transitions from zero events to a positive number.

The intensive component of the hurdle model, on the other hand, applies only to the subset of positive observations, namely those units for which at least one event occurred during the period under consideration. The objective is to estimate the expected number of events among only those units that were activated, i.e., exceeded the threshold for occurrence in the extensive phase. In operational terms, the regression is conducted only on $y_{it} > 0$, adopting the negative binomial regression with random effects.

The theoretical specification is as follows:

$$y_{it} \mid (y_{it} > 0, X_{it}) \sim \text{NegBin}(\mu_{it}, \alpha)$$

Formally, in the negative binomial model with random effects, the dependent variable is assumed to follow a negative binomial distribution with conditional mean μ_{it} and dispersion parameter α.

The conditional mean $\mu_{it} = \mathbb{E}[y_{it} \mid X_{it}, y_{it} > 0]$ is modeled as an exponential function of a linear combination of the explanatory variables. In other words, the expected number of fires is assumed to depend log-linearly on the regressors, according to the following transformation:

$$\log(\mu_{it}) = X'_{it}\beta + u_i$$

or, equivalently,

$$\mu_{it} = \exp(X'_{it}\beta + u_i)$$

where X_{it} is the vector of observed explanatory variables; β is the vector of coefficients to be estimated; and $u_i \sim \mathcal{N}(0, \sigma^2)$ is the random effect term specific to facility i, capturing unobserved heterogeneity at the plant level that persists over time. This logarithmic transformation of the expected mean makes it possible to ensure that μ_{it} is always positive, while at the same time allowing for an intuitive interpretation of the coefficients in terms of expected percentage changes in the number of fires.

In this setting, the estimation is done conditional on the realization of the event, allowing the factors associated with the frequency of the phenomenon to be isolated once it has occurred. The variance of the dependent variable, consistent with the model, is given by:

$$\text{Var}(y_{it} \mid X_{it},\, y_{it} > 0) = \mu_{it} + \alpha\mu^2_{it}$$

where the dispersion parameter $\alpha > 0$ governs the magnitude of overdispersion. Indeed, when $\alpha = 0$, the model reduces to the Poisson case, making the negative binomial a more general and robust extension of it.

Hence, the logic of the hurdle approach lies in its ability to separate and distinctly model two structurally different processes: on the one hand, the transition from the state of absence to the state of presence of the event (extensive component), and on the other hand, the quantification of intensity among those involved (intensive component). This type of modeling is therefore particularly suited to contexts such as the one under consideration.

In light of these theoretical considerations, the hurdle model will be applied to the empirical context under study in order to accurately analyze the relationship between plant pressure and fire incidence. Below, the specification adopted for the two stages of the hurdle model and the variables included in the analysis are described in detail.

Extensive Component

The extensive component is modeled through a logit regression in which the dependent variable is a binary indicator equal to 1 if the facility has had at least one fire in a certain year, and 0 otherwise. This model estimates the probability of experiencing a fire at least once:

$$\Pr(\text{fire\_pos}_{it} = 1) = \frac{\exp(\alpha_0 + \alpha_1 \cdot \ln\_totwt_{it} + \alpha_2 \cdot isol_{it} + \alpha_3 \cdot ratio\_exp_{rt} + \alpha_4 \cdot \ln\_pop_{rt} + \delta_t)}{1 + \exp(\alpha_0 + \alpha_1 \cdot \ln\_totwt_{it} + \alpha_2 \cdot isol_{it} + \alpha_3 \cdot ratio\_exp_{rt} + \alpha_4 \cdot \ln\_pop_{rt} + \delta_t)}$$

For practical reasons, the names of the variables in the equation have been abbreviated, but full definitions of the variables are given below. In particular, $fire\_pos_{it}$ is a binary variable that takes a value of 1 if the facility experienced at least one fire in the year under consideration and 0 otherwise and captures the occurrence event, regardless of the number of fires that actually happened, allowing the estimation of the probability that a facility is involved by at least one incident during the year; $ln\_totalwastetreated_{it}$ is the natural logarithm of the total amount of waste treated at facility i in year t; $isolation_{it}$ is a normalized index that measures the geographical isolation of a facility with respect to the nearest existing one (the higher the index, the more isolated the facility); $ratio\_export_{rt}$ is the share of exported waste out of total generated waste at the regional level; $ln\_population_{rt}$ is the logarithm of the regional population; and δ_t are time fixed effects.

Intensive Component

The intensive component is modeled using a negative binomial regression restricted to observations with positive fire counts only, estimating the expected number of fires among facilities that had at least one fire, handling discretion and count overdispersion:

$$\mathbb{E}[n\_fires_{it} \mid n\_fires_{it} > 0, X_{it}] = \exp(\theta_0 + \theta_1 \cdot \ln\_twt_{it} + \theta_2 \cdot iso_{it} + \theta_3 \cdot ratio\_exp_{rt} + \theta_4 \cdot \ln\_po_{rt} + \delta_t).$$

For practical reasons, the names of the variables in the equation have been abbreviated, but full definitions of the variables are given below. Specifically, num_fires_{it} is the number of fires recorded at facility i in year t; $ln\_totalwastetreated_{it}$ is the natural logarithm of the total amount of waste treated at facility i in year t; $isolation_{it}$ is a normalized index that measures the geographical isolation of a facility with respect to the nearest existing one (the higher the index, the more isolated the facility); $ratio\_export_{rt}$ is the share of exported waste out of total generated waste at the regional level; $ln\_population_{rt}$ is the logarithm of the regional population; and δ_t indicates a set of year dummies (time fixed effects) that capture systematic temporal trends.

The adoption of the hurdle model thus allows the underlying mechanisms of fire probability and frequency to be separated, reflecting more realistically the causal structure of the phenomenon.

4.2.2.a Results of the Analysis of the Relationship between Plant Pressure and Waste Fire Incidence in Italy

For each of the two components of the second part of the analysis, the main estimated coefficients will be reported and interpreted, with particular attention to the role of the variable of interest and the significance of the results obtained.

Results of the Extensive Component

The first component of the hurdle model is estimated through a logistic regression with random effects, in which the dependent variable takes a value of 1 if the facility recorded at least one fire in the year under consideration, and 0 otherwise. This stage allows us to isolate the determinants that influence the probability of occurrence of the event, regardless of the number of fires recorded. In the logit model, the estimated coefficients represent the effect of the independent variables on the logarithm of the ratio of the probability of at least one fire occurring to the probability of it not occurring (log-odds). For example, as shown in Table 16, the coefficient associated with the logarithm of total waste treated is 0.183 ($p < 0.001$), meaning that a unit increase in the amount of waste treated (in logarithms) increases the log-odds of having at least one fire. However, log-odds are not directly interpretable in probabilistic terms, which is why average marginal effects are also calculated.

The marginal effects, shown separately in Table 17, indicate how much the expected probability of the event occurring varies as a specific independent variable changes, holding the others constant. They are obtained by evaluating the derivative of the logistic function with respect to each covariate, averaged over all observations in the sample. In the case of the log of total waste treated, the estimated marginal effect is 0.0201 ($p < 0.001$), indicating that a unit increase in the amount treated (on a logarithmic scale) is associated with an increase of about 2 percentage points in the probability that a facility will record at least one fire in a given year. This difference between coefficient and margin is typical of logit models, where the effect on probability varies nonlinearly depending on the value of the covariates, while the coefficient acts on a constant log-odds scale.

Table 16: Random-Effects Logistic Regression Results: Probability of Experiencing at Least One Fire

Variable	Coefficient	Std. Err.	z	p-value
log(totalwastetreated)	0.183^{***}	0.032	5.83	0.000
Isolation	1.524^{***}	0.440	3.47	0.001
Ratio_export	-23.789^{***}	6.153	-3.87	0.000
log(population)	0.340^{***}	0.093	3.68	0.000
Year = 2017	2.052^{***}	0.274	7.53	0.000
Year = 2018	2.642^{***}	0.271	9.75	0.000
Year = 2019	2.729^{***}	0.271	10.08	0.000
Year = 2020	2.109^{***}	0.273	7.72	0.000
Constant	-11.061^{***}	1.472	-7.54	0.000
Random Effects Parameters				
σ_u	1.193	0.109		
ρ	0.302	0.039		
Model Diagnostics				
Log-likelihood		-1150.6433		
Wald $\text{chi}^2(8)$		185.23 (p = 0.000)		
LR test vs. pooled: $\text{chibar}^2(01)$		86.15 (p = 0.000)		

Note: The dependent variable is a binary indicator equal to 1 if a facility experienced at least one fire in a given year. Coefficients are from a random-effects logistic regression. $^{***}p < 0.01$.

Table 17: Average Marginal Effects from Random-Effects Logistic Regression

Variable	dy/dx	Std. Err.	z	p-value
log(totalwastetreated)	0.0201^{***}	0.0034	5.94	0.000
Isolation	0.1675^{***}	0.0479	3.49	0.000
Ratio_export	-2.6146^{***}	0.6690	-3.91	0.000
log(population)	0.0375^{***}	0.0101	3.72	0.000
Year Dummies				
2017	0.1402^{***}	0.0166	8.46	0.000
2018	0.2158^{***}	0.0186	11.57	0.000
2019	0.2284^{***}	0.0188	12.16	0.000
2020	0.1467^{***}	0.0169	8.66	0.000

Note: dy/dx represents the average marginal effect on the probability of experiencing at least one fire.

*p<0.10, **p<0.05, ***p<0.01

The same reasoning applies to the other covariates. The isolation index shows a coefficient of 1.52 ($p < 0.001$), and a mean marginal effect of 0.168: this implies that, all things being equal, a plant located in a more isolated area has a higher probability of fire by about 16.8 percentage points than one that is less isolated. Export, on the other hand, has a negative coefficient (-23.79) and is significant, with a marginal effect of -2.61: greater reliance on waste exports is thus associated with reduced fire probability, consistent with the idea that exports relieve pressure on the local plant system. Regional population also exerts a significant positive impact (with a marginal effect of +0.037), suggesting that a denser demographic environment may amplify the risk of critical events.

Finally, the coefficients of year fixed effects indicate that, other things being equal, the probability of fires increased significantly starting in 2018, peaking in 2019. This trend is consistent with the hypothesis of a shock effect due to the implementation of the Chinese ban, which altered the balance of the disposal system, generating an increased risk of congestion. In summary, the first stage of the hurdle model confirms the existence of a robust link between plant pressure and fire risk, both structurally and temporally. In addition, diagnostic statistics, such as the log-likelihood value (-1150.6), Wald test ($\chi^2 = 185.23$, $p < 0.001$), and likelihood-ratio test for significance of random effects ($chibar^2(01) = 86.15$, $p < 0.001$), confirm the overall robustness of the logit model. In particular, the significance of the $\rho \neq 0$ test justifies the inclusion of random effects at the plant level, signaling that there is unobserved variability between plants that affects fire probability. This strengthens the reliability of the estimates produced in the extensive stage of the model.

Results of the Intensive Component

The second component of the hurdle model is estimated on a subset of the dataset consisting exclusively of facilities that have experienced at least one fire in a given year. This stage aims to model the intensity of the phenomenon, i.e., the expected number of fires conditional on the event in which at least one fire has occurred. To do so, a negative binomial regression with random effects is employed, which allows for proper treatment of the dependent variable of count type, which is discrete and subject to overdispersion, as well as accounting for unobserved heterogeneity at the plant level. In this model, the estimated coefficients reflect the impact of covariates on the logarithm of the expected number of fires. For example, as shown in Table 18, the coefficient associated with the log of total waste treated is 0.033 ($p = 0.075$), implying that a unit increase (in logarithms) in the amount of waste treated is associated with an increase in the log of the expected number of fires. However, since the effect is expressed in logarithmic terms, its direct interpretation is not straightforward in terms of the expected level of the dependent variable. For this reason, marginal effects are also calculated.

Marginal effects report the impact of each covariate directly on the expected number of fires, holding the other variables constant and calculating the derivative of the prediction function with respect to each predictor. In the case of the log of total waste treated, the estimated marginal effect is 0.033 (Table 19), i.e., each unit increase in the amount treated (in log) is associated, on average, with an increase of about 0.033 fires among facilities that have already experienced at least one event. In short, while the logarithmic coefficient describes the impact in relative (log-linear) terms, the marginal effect allows the result to be interpreted in terms of the expected change in the actual count, and is therefore more easily interpretable.

Table 18: Negative Binomial Regression (Number of Fires > 0) with Random Effects at the Facility Level

Variable	**Coefficient**	**Std. Err.**	**z**	**p-value**
log(totalwastetreated)	0.033*	0.019	1.78	0.075
Isolation	0.164	0.239	0.69	0.493
Ratio_export	-3.728	4.146	-0.90	0.369
log(population)	0.150**	0.068	2.19	0.028
Year = 2017	0.119	0.235	0.50	0.614
Year = 2018	0.497**	0.229	2.17	0.030
Year = 2019	0.397*	0.228	1.74	0.082
Year = 2020	0.288	0.233	1.24	0.215
Constant	-0.228	1.102	-0.21	0.836
Random Effects Parameters				
ln(r)	4.116	0.351		
ln(s)	1.857	0.188		
r	61.303	21.520		
s	6.403	1.204		
Model Diagnostics				
Log-likelihood				-825.1991
Wald chi^2(8)				21.64 (p = 0.0056)
LR test vs. pooled: chibar^2(01)				98.82 (p = 0.000)

Note: The dependent variable is the number of fires, restricted to observations with strictly positive fire counts. The model includes random effects at the facility level and year fixed effects. The sample size is 521 observations.

*p<0.10, **p<0.05, ***p<0.01

Table 19: Average Marginal Effects from Random-Effects Negative Binomial Model

Variable	**dy/dx**	**Std. Err.**	**z**	**p-value**
log(totalwastetreated)	0.033*	0.019	1.78	0.075
Isolation	0.164	0.239	0.69	0.493
Ratio_export	-3.728	4.146	-0.90	0.369
log(population)	0.150**	0.068	2.19	0.028
Year Dummies				
2017	0.118	0.235	0.50	0.614
2018	0.497**	0.229	2.17	0.030
2019	0.397*	0.228	1.74	0.082
2020	0.288	0.233	1.24	0.215

Note: dy/dx values represent average marginal effects on the predicted number of fires, restricted to observations with strictly positive fire counts.

*p<0.10, **p<0.05, ***p<0.01

Regarding the other covariates, the results confirm the positive and significant role of the regional population (coefficient = 0.15, $p = 0.028$), indicating that facilities located in denser demographic settings tend to experience more fires, conditional on their occurrence. This result could reflect greater logistical or administrative pressure in more populated areas. In contrast, isolation and exports are not significant in this second stage. This suggests that these characteristics predominantly influence the probability of a fire occurring, but not the frequency of fires once the phenomenon has already occurred.

Overall, this second estimate reinforces the idea that increased plant pressure as measured by treated volumes is associated not only with an increased likelihood of fires (extensive phase), but also with their increased intensity (intensive phase). However, the effect appears smaller and less stable in the conditional subset, probably due to the smaller sample size. Looking at the model adequacy statistics, although the number of observations is lower, there are useful insights: the Wald test (χ^2 = 21.64, p = 0.0056) confirms that the model as a whole is significant, while the likelihood-ratio test ($chibar^2(01)$ = 98.82, $p < 0.001$) indicates the significance of random effects, justifying the use of the panel structure. However, compared with the previous specification, the overall significance appears to be attenuated, confirming that the intensive phase of the analysis captures weaker and unstable effects, likely related to the lower observable variability in the conditioned subset.

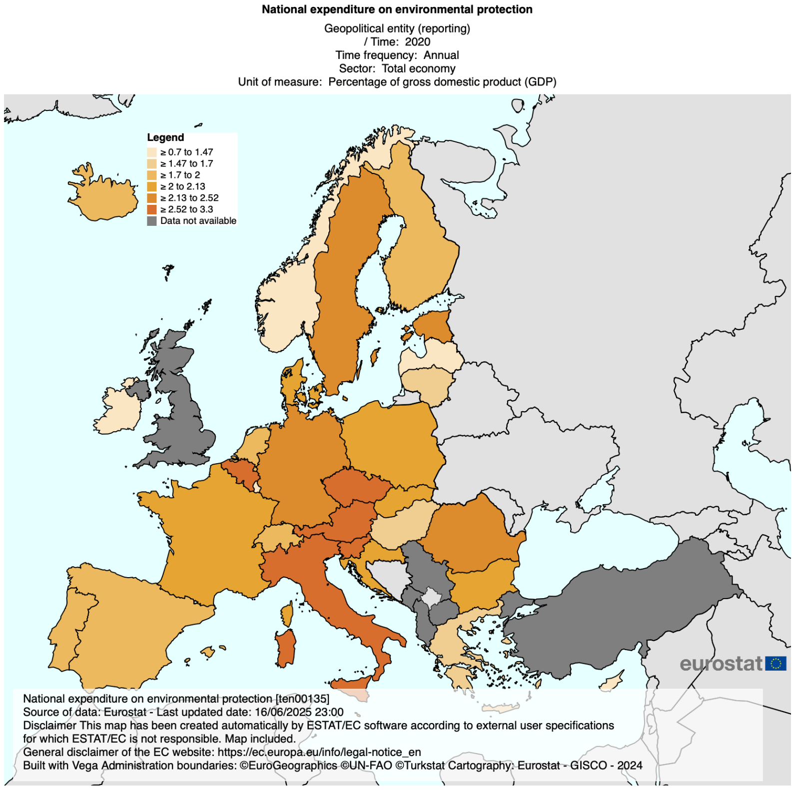
5 Environmental Protection Expenditure

The results from the empirical analysis show systematically and consistently that increased operational pressure on waste treatment plants is associated with increased likelihood and frequency of fires. This link suggests that operational load is not simply an indicator of managerial performance, but actually represents an environmental and systemic risk factor. As such, this finding calls for a broader reflection that goes beyond just the technical dimension of plant operation and directly involves public policy, public investment levels in prevention, and the system's ability to anticipate and contain the negative externalities associated with infrastructure overload.

In this context, it is particularly useful to contextualize the issue of the vulnerability of the waste management system within the broader framework of public spending on environmental protection. The latter constitutes a crucial policy tool in mitigating upstream environmental risks, preventing crisis situations, and ensuring structural resilience of facilities and territories. According to Eurostat, environmental protection expenditure can be defined as "the economic resources devoted to prevention, reduction, and elimination of pollution and any other degradation of the environment". At a theoretical level, several studies confirm the importance of environmental investments in promoting not only ecological but also economic benefits. Already Porter and van der Linde (1995) had pointed out that well-designed environmental regulations could stimulate innovation, helping to improve firms' production efficiency and, in some cases, even enhancing their competitiveness. More recently, Akdag et al. (2024) showed that public spending on environmental protection, especially in the European context, is significantly more effective than environmental taxes in reducing greenhouse gas emissions, thus reinforcing the idea that smart allocation of public resources can generate positive environmental as well as economic payoffs.

More specifically, spending on environmental protection can be interpreted as a form of public insurance against large-scale harmful events, performing a stabilizing function for the economy and helping to reduce social and health risks associated with environmental crises. In the Italian context, this role is particularly relevant in light of the geographic, regulatory, and infrastructural complexity of the waste management system, as well as the tensions that have emerged as a result of external shocks such as China's 2018 waste import ban. In other words, investing in environmental protection does not simply mean acting after damage has occurred, as in the case of putting out a fire or cleaning up a contaminated site, but rather adopting prevention policies that aim to reduce the likelihood of such risks occurring in the first place. This approach reflects a strategic view of environmental expenditure, in which the value of investments is also measured in terms of strengthening resilience and containing the structural vulnerability of the system.

In this light, this insight is intended to offer a complementary perspective to the empirical findings discussed above by looking descriptively at some of the evidence related to public spending on environmental protection. While this section does not constitute a formal economic analysis of costs, it allows the risk dynamics revealed in the empirical section to be contextualized within a broader framework that includes resources devoted to the management and prevention of environmental impacts.



National expenditure on environmental protection [ten00135]
Source of data: Eurostat - Last updated date: 16/06/2025 23:00
Disclaimer This map has been created automatically by ESTAT/EC software according to external user specifications for which ESTAT/EC is not responsible. Map included.
General disclaimer of the EC website: https://ec.europa.eu/info/legal-notice_en
Built with Vega Administration boundaries: ©EuroGeographics ©UN-FAO ©Turkstat Cartography: Eurostat - GISCO - 2024

Figure 15: National expenditure on environmental protection in Europe, year 2020. *The map shows annual spending on environmental protection expressed as a percentage of gross domestic product (GDP) for each European country in 2020. The data refer to the entire national economy and are divided into six expenditure intensity classes. Higher levels (over 2.5% of GDP) are observed in countries such as Belgium, Austria, and Italy, while many other central and southern European countries are in lower ranges. Data are not available for countries shown in dark gray. Source: Eurostat.*

Figure 15 shows the distribution of national spending on environmental protection in Europe, expressed as a percentage of gross domestic product (GDP) for the year 2020. This indicator is a concise but effective measure of each country's focus on environmental policies through the allocation of economic resources. Italy is at the top end of the European ranking, with public environmental spending between 2.52% and 3.3% of GDP, well above the EU average. This figure, in relative terms, signals a substantial and structural financial commitment to environmental protection, higher than the one recorded in many other western and southern European countries. Italy's position is particularly relevant considering that environmental spending includes a variety of interventions related to waste management, air, water and soil protection, pollution prevention, and environmental risk reduction. Placement in the top group of European countries suggests that, at least in terms of budgets, Italy recognizes the strategic importance of these activities. Moreover, the geographical comparison shows a high degree of variability within the European Union: while some central and northern countries (such as Austria, Belgium, and the Czech Republic) show levels similar to the Italian one, many eastern and southern European economies are at significantly lower levels.

To better understand how this high Italian expenditure is distributed, it is useful to look at its internal composition over time. A closer look at the composition of environmental spending in Italy between 2016 and 2020 (Figure 16) shows that the dominant spending item is consistently waste management, which takes up a significant share of the total each year, confirming the central weight

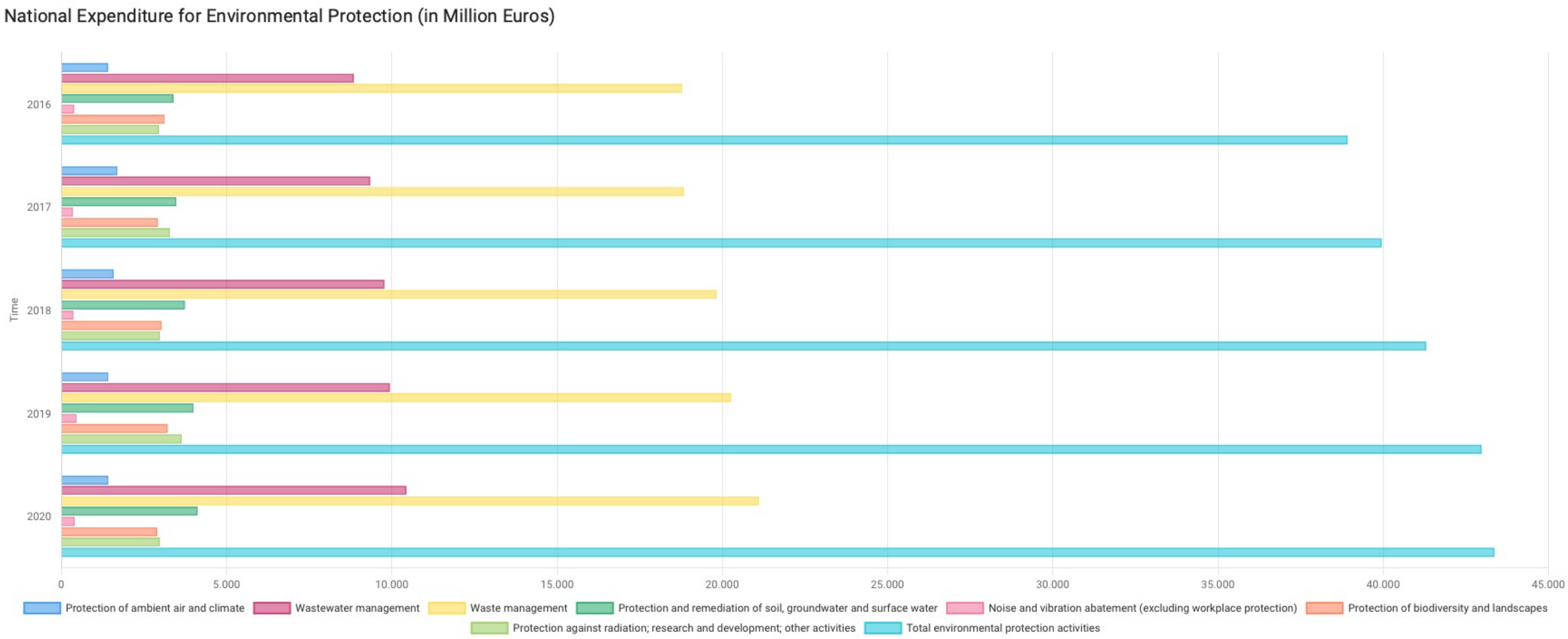


Figure 16: Italian national expenditure for environmental protection by functional category, years 2016-2020. *The graph shows trends in overall environmental spending and disaggregated into different functional categories in Italy from 2016 to 2020. The main items include waste management, wastewater management, and air and climate protection, as well as spending on soil and water protection, biodiversity, landscape, and noise abatement. Total spending on environmental protection shows steady growth over the period, driven mainly by investments in waste and wastewater management. Source: Istat.*

of this sector in national environmental strategies. Next in terms of magnitude are expenditures on wastewater management and the protection and remediation of soil, groundwater, and surface water. Smaller, but still present, are the resources devoted to air and climate protection, noise and vibration containment, and biodiversity and landscape protection.

Overall, total spending on environmental protection in Italy has followed a gradually increasing trend over the 2016-2020 period, rising from just under 38 billion euros to more than 42 billion. This growth appears particularly relevant starting in 2018, which is also a key year for the dynamics observed in the empirical analysis. It is plausible that this increase reflects, at least in part, the effect of external shocks such as the ban on China's waste imports, which generated sudden pressure on the domestic treatment system. In the absence of international outlets for certain waste fractions, public institutions faced an increase in internally managed volumes, resulting in the need to strengthen treatment and disposal infrastructures, improve collection and monitoring systems, and contain the risk of saturation or malfunction of facilities. Among all expenditures, waste management is consistently confirmed by a wide margin as the largest component of Italy's environmental budget. This figure is not surprising considering that the waste sector represents one of the areas with the highest operational impact and risk exposure, both logistically and environmentally. The costs of collection, transportation, treatment, and disposal, combined with those associated with emergency management, such as fires or irregular storage, make this sector particularly sensitive to systemic imbalances or sudden changes in flows. In this context, the high expenditure can also be read as an indirect indicator of the management complexity of the system and the need to maintain its functionality under conditions of increasing pressure.

From an analytical point of view, this evidence helps reinforce the interpretation that the system's ability to absorb additional waste loads, such as those generated by the import ban, depends not only on the physical endowment of facilities, but also on public investment in their adaptation, maintenance, and upgrading. The fact that waste management steadily represents the main item of environmental spending highlights that Italian environmental policies actually recognize the central role of this sector for the overall stability of the system. High and rising spending, if well directed, can play a crucial role in preventing critical phenomena, increasing the resilience of the treatment system and its ability to absorb future shocks.

To better understand who financially bears the burden of waste management, it is necessary to disaggregate spending by institutional sector, distinguishing between government, corporations, and households (Figure 17). This reading makes it possible to assess how economic responsibilities are distributed among the different actors and what the relative contribution of each component is in supporting a sector that is structurally central to environmental protection.

Corporations represent the dominant component of spending each year, followed by households, which support a large and stable share over time. Much smaller, but not negligible, is the contribution of government and non-profit institutions, whose incidence remains low for almost the entire period, except for a visible increase in 2020. These data raise an interesting point. Unlike other areas of environmental spending, where public funding is often the main component, waste management in Italy seems to rely on a mostly privatized and decentralized model, where the cost of the service is largely covered by corporations and households. This setting may reflect well-established regulatory

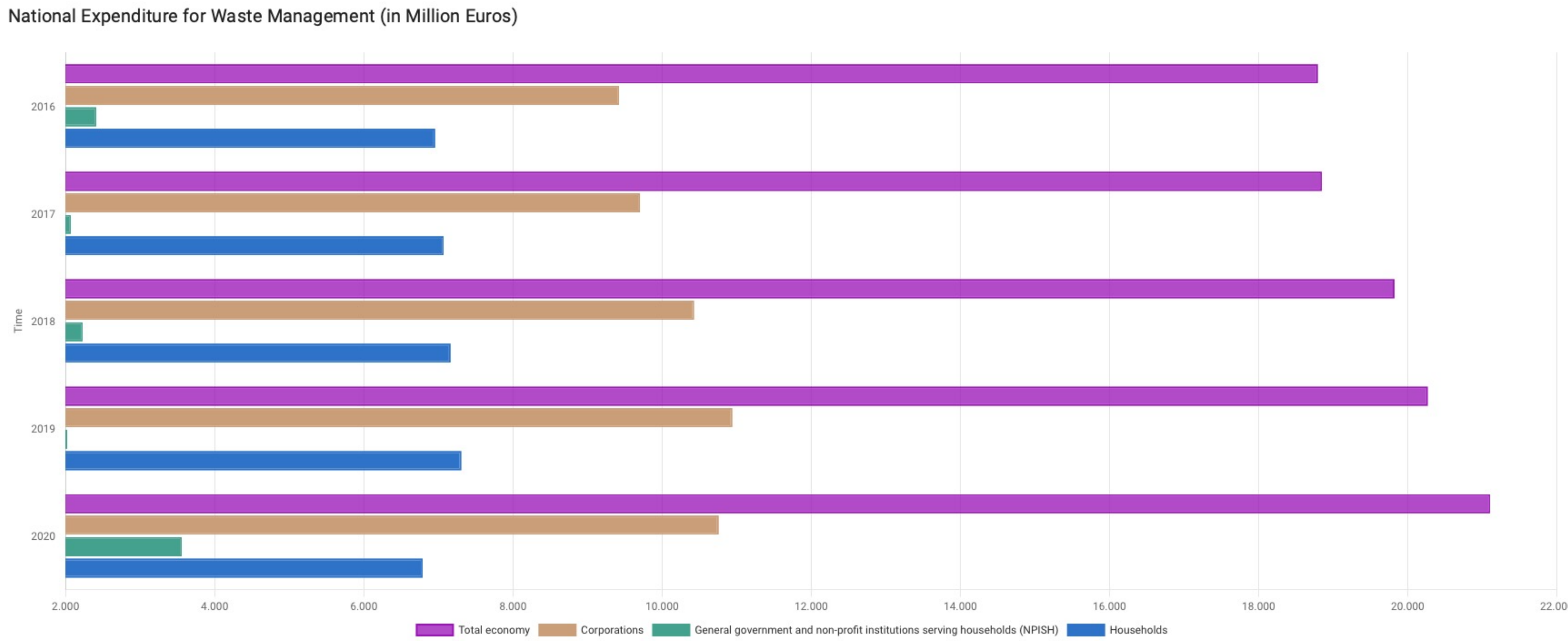


Figure 17: National expenditure for waste management in Italy by institutional sector, years 2016-2020. *The graph shows the distribution of waste management spending in Italy by sector: households, businesses, government, and non-profit institutions serving households (NPISH), showing the overall total for each year. It is observed that the main share of spending is borne by businesses and households, with public participation limited but growing in 2020. Overall spending shows a gradual increase over the five-year period, peaking in 2020. Source: Istat.*

choices, such as the *polluter pays* principle, but it also highlights a potential structural limitation. In situations of shock, imbalance, or systemic crisis, the capacity to respond in a coordinated manner may be weakened, precisely because it is not the State that exercises direct financial control over the sector. In 2020, an increase in the public sector's share of waste management expenditures is observed. In response to the Chinese shock, the role of institutions has become more active, both in terms of emergency response and through enhanced surveillance, prevention, and operational management activities. The increase in public spending can thus be read as a signal of institutional reaction to a situation of environmental stress, but also as a beginning of re-centralization in the financing model.

Moreover, the fact that households bear a significant and stable share of the expenditure on waste management clearly highlights the social dimension of this sector. Indeed, waste management is not only a technical or environmental issue, but also involves direct economic impacts on citizens through tariffs, taxes, and cost-covering mechanisms at the local level. This aspect helps to reinforce the idea that the resilience of the system depends not only on the adequacy of facilities or the level of overall spending, but also on the structure and balance of the financing model, particularly with regard to the distribution of the economic burden among public actors, businesses, and households. In an context subject to environmental shocks and increasing pressures, such as the one analyzed here, the system's responsiveness is also linked to the economic sustainability and fairness of the contribution required from the different stakeholders.

These insights into the economic and institutional structure of waste management, together with the empirical evidence on the link between operational pressure and fire risk, provide a solid basis for considering some policy implications. In this perspective, it is possible to outline some recommendations aimed at improving the effectiveness and resilience of the system through a more strategic and targeted use of public environmental spending.

The results of the empirical analysis confirm that increased operational pressure on waste treatment plants is systematically associated with increased fire risk. This evidence suggests that environmental policies cannot be limited to responsive or ex-post interventions, but must include structural strategies to prevent and strengthen the plant system. In light of this, a first recommendation relates to the need to stabilize and increase public spending on waste management, ensuring that a significant share is directed not only to operational coverage of costs but also to targeted investments aimed at reducing the vulnerability of the system. These include, for example, upgrading treatment capacity in the most exposed areas, technological modernization of existing facilities, and the introduction of more advanced monitoring and surveillance mechanisms. A second area of intervention concerns the rebalancing of the financing structure, which today is heavily reliant on firms and households. Increased public sector participation, already observable from 2020, could strengthen systemic resilience and ensure more effective coordination in response to sudden shocks or structural imbalances.

Useful evidence comes from the transportation sector, where the management of environmental externalities has posed similar challenges to those faced in the governance of the waste system. In both cases, the fragmentation of responsibility, the difficulty of monitoring individual behavior, and the systemic nature of the risks make tools such as Pigouvian taxes ineffective. Jacobsen et al. (2023), analyzing the U.S. transportation sector, show that in settings where direct taxation is technically or politically complex, binding technical standards and well-designed regulatory policies can significantly reduce environmental externalities. This approach is also particularly relevant to the waste sector, where, as the results of this analysis show, operational pressure on facilities is a real risk factor for environmental safety. From this perspective, the adoption of mandatory minimum residual capacity standards, predictive monitoring systems, and constrained investments in technological adaptation could be an effective and realistic means of containing systemic risks. The case of transportation suggests that even in the presence of strong institutional constraints, ex-ante regulatory measures can generate both environmental and economic benefits.

Finally, a key element for strengthening the system concerns the structural integration of prevention within public expenditure planning. Preventing critical events such as fires in treatment plants cannot be considered an accessory objective or left to occasional and reactive measures. In contrast, it is necessary to develop a systemic and anticipatory strategy that can identify risk conditions in advance and intervene before they result in harmful events. This strategy must be based on robust analytical tools, such as monitoring systems, spatial indicators of plant pressure, and predictive analyses based on historical data.

The results of this study clearly show that there is a significant relationship between plant overload and increased fire risk. This kind of knowledge represents a valuable source of information that should be enhanced through the creation of public decision support mechanisms aimed at guiding resource allocation in a selective manner. This means not only allocating funds to the most exposed areas, but also strengthening the planning capacity of local authorities, supporting technological renewal, and improving the geographical distribution of facilities. From this perspective, prevention is a strategic investment capable of reducing future risks and ensuring the resilience of the environmental system in the medium to long term.

To sum up, when public spending on waste management is oriented preventively and strategically, it is one of the most effective tools for reducing environmental risks, containing long-term costs, and increasing the safety and sustainability of the entire system (Akdag et al., 2024). Future policies should take this evidence into account by adopting an integrated view of environmental spending that values not only the ecological impacts, but also the systemic and economic impacts associated with the stability and functionality of the treatment system.

6 Conclusions

This thesis rigorously examined the relationship between pressure on waste treatment plants and fire incidence in Italy, in the context of the changes brought about by China's 2018 ban on waste imports. The two-phase empirical approach allowed, on the one hand, to assess whether the ban actually led to an increase in the volumes of waste treated locally; and, on the other hand, to analyze the extent to which this increase in plant pressure has affected the likelihood and frequency of fires recorded at Italian plants.

The results of the first phase, aimed at estimating the effect of the Chinese ban on plant pressure, show an increase in treated waste volumes starting in 2018, consistent with the assumption of an exogenous shock to the system capacity. However, this effect is not statistically significant, probably mainly due to the limited availability of granular data. Consequently, while it cannot be rigorously stated that the ban caused a systematic increase in plant pressure, a positive trend is nonetheless observed, suggesting that with more disaggregated data perhaps the link would be significant.

In contrast, the second phase of the analysis provides robust and statistically significant results. In the estimation conducted applying the hurdle model, it consistently emerges that an increase in treated waste is associated with a higher incidence of fires at the facilities. Operational load appears to be a relevant and statistically significant determinant. This implies that, regardless of its exogenous origin (and the possibility of relating it directly to the ban), pressure on Italian facilities is a concrete risk factor, capable of increasing both the frequency and severity of events. Empirical evidence thus suggests that overloading of treatment sites is not only a management problem, but also poses a threat to environmental safety, requiring priority attention from institutions.

From this perspective, the analysis of environmental protection expenditure in Italy helps place the empirical results within a broader interpretive framework, in which waste management emerges not only as an operational matter, but also as a strategic lever of prevention. Stable and targeted investments in waste cycle management, especially in plant capacity, monitoring, and maintenance, can in fact structurally reduce the vulnerability of the system, strengthening its resilience against overload conditions or exogenous shocks. This perspective confirms that proper allocation of public resources, in addition to responding to immediate needs, can make a major contribution to reducing systemic and environmental risks.

These findings carry major implications for the design of public policies in the waste management sector. The results suggest that pressure on facilities cannot be considered just a technical-operational indicator, but represents a real environmental and systemic risk factor. Consequently, monitoring of input flows and saturation of authorized capacity should take a central role in prevention strategies, alongside formal safety and control measures. First, it must be recognized that the effectiveness of the Italian plant network depends not only on the availability of overall capacity, but also on its geographical distribution. The high concentration of plants in some areas of the country, compared with structural deficiency in others, generates imbalances that result in localized overloads and increased vulnerability. This highlights the urgent need to promote more stringent forms of inter-regional coordination and to incentivize investment in new facilities in contexts that have so far been underdeveloped. Second, there is an emerging need to strengthen the operational resilience of the supply chain. This implies the adoption of predictive flow-monitoring tools capable of warning of plant stress situations in real time, as well as policies aimed at reducing storage times and encouraging faster rotation of treated materials. Advanced digital traceability systems, integrated at the national level, can also help increase transparency along the treatment chain, facilitating the detection of unusual practices and discouraging the use of improper or illicit management. Finally, it should be considered that a non-negligible proportion of the fires analyzed involved properly authorized facilities, highlighting that regulatory compliance alone is not a sufficient condition to guarantee the safety of the system. This reinforces the need for a preventive approach by regulators, capable of combining ex-post controls with actions to strengthen operational capacity and promote uniform minimum technical standards throughout the country.

Lastly, this work opens several promising directions for the development of future research. A first and natural extension would be to strengthen the causal identification of the effect of the 2018 Chinese ban through the use of more granular data. In particular, the availability of facility-level information on the volumes of waste actually exported before and after the ban, as well as the amount of waste treated by type, would allow for the construction of more accurate measures of shock exposure and the identification of more credible treatment and control groups, so as to improve the precision of estimates and the reliability of inferences. A further extension could involve analyzing the economic and social costs associated with fires at treatment plants. Assessing the impact of these events in terms of environmental damage, cleanup expenses, service disruptions, and reputational repercussions for local authorities would be a key element in estimating the overall burden of the phenomenon and strengthening the evidence to support prevention interventions. In this sense, a cost-benefit analysis of policies to reduce pressure on facilities could be an important applied contribution to environmental economics, as well as a useful tool to guide a more efficient allocation of public resources across prevention, maintenance, and system upgrading interventions.

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