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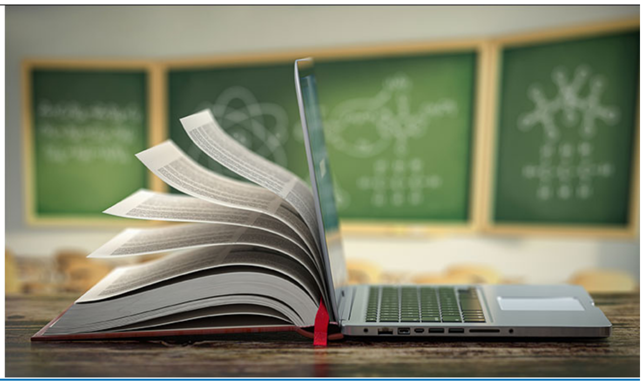

Waste recycling as an aspect of the transition to a circular economy

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Abstract. A necessary condition for a successful transition to a circular or closed economy is the creation of sufficient capacity for sorting and recycling of production and consumption waste. According to experts, annually more than 10 million tons of tires go out of use in the world, only in Russia every 4–5 years the increase in used tires will be about 2 million tons, which creates serious environmental and economic problems. This research is aimed at solving the problem of recycling accumulated and formed waste tires. The article provides a comparative analysis of tire recycling methods, proves the choice of pyrolysis method and estimates the environmental and economic efficiency of the project of a plant for processing used tires by pyrolysis.

1. Introduction

Since 2014 extensive reforms in the sphere of the state environmental stewardship management has been introduced in the Russian Federation in order to ensure environmental safety. The most serious legislative changes have affected the improvement of the production and consumption waste management.

Despite the measures are being taken, the volume of production and consumption waste increases in the Russian Federation. In contrast, the volume of used and neutralized waste does not show positive dynamics [1]. The dynamics of production and consumption waste generation and use in the Russian Federation is given in the Figure 1.

According to the Federal State Statistic Service, in 2018, the volume of production and consumption waste in the Russian Federation reached 7266.0 million tons (in 2017 it was 6220.6 million tons). The share of used and neutralized waste in 2018 was 3818.4 million tons or 52.6% of the total volume (in 2017 it was 3264.5 million tons, which represented 52.2%).

In 2018, the volume of waste sent for storage or disposal is 3575.4 million tons (in 2017 it was 3024.5 million tons).

Waste storage in 2018 amounted to 2546.1 million tons. According to waste hazard classes, hazard class V dominated in the total volume of waste storage (99.7%).

By industry, in 2018, the largest amount of waste was stored at mining enterprises (95% of the total amount of waste stored).

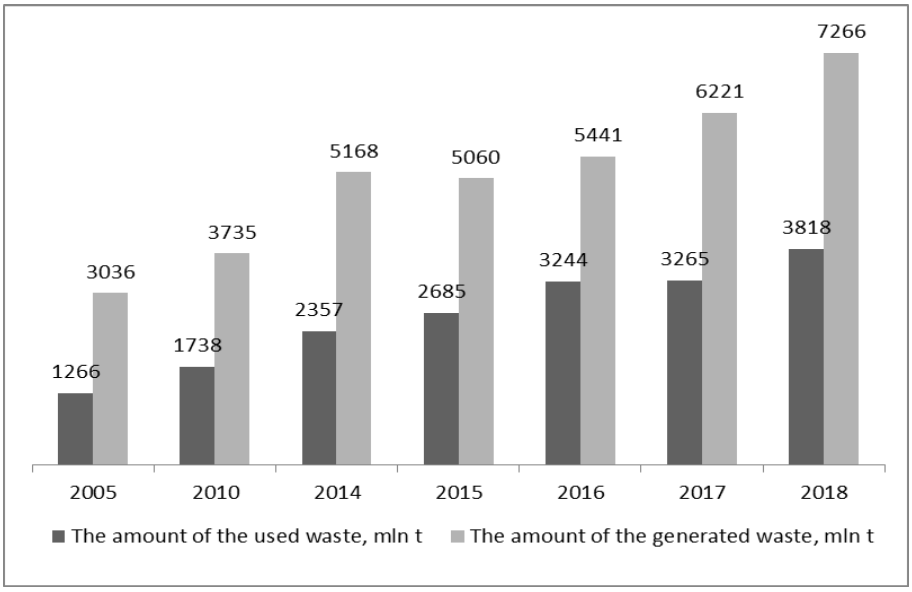

Figure 1. The dynamics of formation and use of production and consumption waste.

In 2018, the volume of production and consumption waste removed to burial facilities amounted to 1029 million tons (in 2017 it was 826 million tons).

The total volume of accumulated production and consumption waste was about 38.1 billion tons by the end of 2018, 99% of which is non-hazardous waste [1, 2].

The main strategic document for improving the environmental situation in Russia and creating comfortable living conditions in the country is the National Project “Ecology” [3], the implementation period of which is defined at the end of 2024. The main aim of the «Federal project in the field of waste management» as part of the national project is to form a comprehensive waste management system and create conditions for recycling of all production and consumption waste prohibited for disposal.

The financing for the national project specifically in the part of the Federal Project Integrated Strategy for Municipal Solid Waste (MSW) Management is 296223.8 million rubles, which includes 107864.8 million rubles from the federal budget.

The next comprehensive document is the Environmental Security Strategy of the Russian Federation for the period until 2025 [4], the target indicators of which are following:

- the specific volume of generated waste of all hazard classes per unit of gross domestic product at the end of 2025 is 62 tons / million rubles (current value is 66 tons / million rubles);

- the share of disposed and neutralized waste of all hazard classes from the total amount of generated waste of all hazard classes at the end of 2025 is 50%(current value is 45%, forecast).

In addition, a legal framework has been established for the implementation of extended producer responsibility (EPR) for waste disposal. The list of finished goods was approved, including packaging, to be disposed of after they have lost their consumer properties. Waste disposal standards for the use of goods for 2018 are 20%, for 2019 are 25% and for 2020 are 30%. Environmental fee rates are set for producers and importers of goods that do not provide independent disposal of waste from the use of goods. In total, 54 groups of products are subject to recycling. So, manufacturers and importers are required to pay an environmental fee if they do not comply with the recycling standards.

The ROP was adopted in Russia in 2014 in order to encourage recycling of goods and packaging, but at this stage it is not actually working. Now the concept of ROP is undergoing serious improvements and refinement. The expected income of environmental fee was up to 136 billion rubles but now no more than 2.5 billion rubles of the environmental fee are being collected from business per year.

2. Analysis of used tires recycling: current situation

Waste of hazard class V account for the major share of waste generated in the Russian Federation. Despite this, it is more critical to recycle each type of waste separately. The authors have discussed the problem of the production and consumption waste recycling in various areas [5–7]. This research is aimed at solving the problem of recycling accumulated and generated waste tires. Used tires, cameras and other rubber products are recognized as waste of hazard category IV. Used tire is a valuable secondary raw material containing 65–70% of rubber, 15–25% of carbon black, 10–15% of metal, so its effective recycling can solve the accumulated environmental problems and ensure high profitability of processing plants.

Rapid motorization has led to the serious problem of accumulation of used tires in different countries. In the United States, the annual volume of used tires exceeds 4 million tons, with about 2 billion waste tires already accumulated. In England, the volume of used tires is more than 500 thousand tons, in Japan it makes up to 1 million tons, in Germany is about 600 thousand tons, in Italy reaches more than 400 thousand tons. In the CIS countries, more than 50 million tons of used tires are accumulated and currently more than 250–300 thousand tons are formed annually. The recycling rate of waste tires abroad varies very widely and reaches 100 % in some Western European countries (table 1). Used tires accumulate in large and small car services, tire repair centers and in the private sector. Most industrial countries have programs and methods that support the collection and recycling of used tires. However, their evacuation, disposal and incineration, which takes place in order to reduce their harmful impact on the environment, are ineffective.

Table 1. Comparative analysis of waste tire management in foreign countries [8].

Country	Used tires, th. tones (per year)	The number of tires sent to landfills, %	Used for energy, %	Tire retreading, %	Getting rubber crumb, %	Export, %	Other, %
Germany	582	0	36.4	12.9	34.5	14.4	1.7
England	527	4.6	35.5	7.4	39.5	5.5	7.6
Italy	424	0	55.6	6.7	28.5	4.0	5.2
France	457	0	49.7	7.7	27.4	10.9	4.4
USA	4039	12.1	47.6	–	32.1	2.5	–
Japan	1000	7.8	64.3	5.6	10.5	11.5	0.3

According to experts, annually more than 10 million tons of tires go out of use in the world. According to the data of the Research Institute of the Tire Industry (SRC “TRI”), annually about 1 million tons of tires go out of use in Russia [9]. The volume of used tires will increase with the growth of freight and road transport.

The volume of tire production, as one of the main types of rubber products, in the Russian Federation is shown in Table 2 [10].

Table 2. The volume of tire production in the Russian Federation.

Name of the Indicator	2017 year	2018 year
Tires and cameras, mln. pcs	65.1	67.5
including:		
for buses, trolleybuses and trucks	7.8	7.8
for cars	44.5	47.6
for agricultural machinery; other	1.9	1.7
for motorcycles or bicycles	0.9	0.8

According to the Federal State Statistic Service, the number of own cars in the Russian Federation per 1000 people is 305 [11]. The average service life of a car tire is about 4–5 years [12, 13]. In this way, the increase of used tires is about 1.2 million tons every 4–5 years, and it makes up to 2 million tons if we take into account freight transport.

In Russia, tire recycling is a serious environmental and economic problem. Used tires are stored in landfills, garbage collectors, placed in natural areas, and accumulated along roads. At the same time, there is land alienation, soil and water pollution. Used tires are flammable. When they burn, harmful combustion products of the I and II waste hazard classes are thrown into the air. From 1 ton of waste tires about 270 kg of soot and 450 kg of toxic gases, as well as carcinogens, are emitted into the atmosphere. Tires are hardly biodegradable. The decomposition time of a rubber tire is more than 100 years.

3. The basic methods of used tires recycling

Nowadays, the development of environmentally friendly technologies for recycling used tires is being intensively carried out all over the world, and the first positive results have already been achieved. These studies include several unrelated areas, each of which has its own advantages and disadvantages.

In world practice, there is a variety of methods processing waste tires. Among the basic methods are incineration, reclaim, crushing, recovery, thermal liquefaction, the use of tires without preliminary preparation and pyrolysis [14–17].

In this research the authors have analyzed tire recycling methods in order to determine the safest and most promising method (table 3). As a result of the analysis, the authors concluded that pyrolysis is the most effective method.

Table 3. Comparative analysis of tire recycling methods.

Criteria	Recycling method					
	Tire recycling into reclaim	Tire recycling into crumb	Microwave pyrolysis	Classic pyrolysis	Gasification	Incineration
Further processing of processed products for sale	Necessary	Necessary	Not necessary	Not necessary	Necessary	No
Recycling of processed products after the end of their service life	Necessary	Necessary	No	No	No	No
Industrial experience	Yes	Yes	Yes	Yes	Yes	Yes
Processing speed	Low	Low	High	Medium	High	-
Environmental factors	Rubber crumb dust, organic oil, inorganic salt	Rubber crumb dust	Carbon dioxide	Carbon dioxide	Carbon dioxide, carbon monoxide	Sulfur oxide, aromatic hydrocarbon, condensed aromatic hydrocarbon, chlorine derivatives, etc.

The table has been compiled by the authors.

Pyrolysis helps to significantly lower pollutant emissions such as sulfur dioxide, nitrogen oxide, carbon monoxide because it is implemented with the lack of air. The following components are formed in the pyrolysis process: carbon black, steel, pyrolysis liquid and pyrolysis gas. In comparison with other methods, these components with energy and economic potential do not need any further processing. This method environmentally has undeniable advantages and allows saving valuable hydrocarbon raw materials. One of the advantages of pyrolysis is also its environmental safety. Based on the tire composition and analysis of the pyrolysis process, we can conclude that the main environmental impact during pyrolysis will be the release of carbon dioxide when heating the crucibles.

According to the data [18], the composition of the pyrolysis gas is represented by the following components: methane (~ 32.2%); ethane (~ 2.5%); butane (~ 1.4%); ethylene (~ 11.2%); pentane-heptane mixture (~ 10%); carbon monoxide (~ 12.2%); carbon dioxide (~ 6.8%); hydrogen and nitrogen-containing components (~ 25%). The total carbon dioxide emissions from heating the crucibles with pyrolysis gas will be approximately 279 kg.

4. Estimation of the environmental and economic efficiency of a project for the processing of car tires by pyrolysis

The main goal of the project is to create a waste rubber goods recycling facility to solve the problems of recycling car tires and reduce the negative impact of waste on the environment.

The following environmental benefits are expected from the project: an increase in the share of waste tire recycling; an annual decrease of waste tires taken to landfills by 650 tons (based on the plant's capacity); economic and environmental benefits. The characteristics of the project products are shown in Table 4.

Table 4. Characteristics of the finished products

Component	Characteristics	Usage
Carbon black	Carbon black is further processed (flotation) to desulfurize the product or is sold as a finished product	Tire industry, automotive industry, paint production, tire tread repair, pretreatment of highly polluted waste water, production of modifiers and fillers for asphalt mix
Steel	High quality scrap specifications	Direct handling
Pyrolysis gas	Components of the pyrolysis gas: - alkanes up to 40% - alkenes up to 20–25% - hydrogen 15–20% - nitrogen up to 20% - carbon monoxide ≤12% [10]	Pyrolysis equipment heating, in the drying process, compression in cylinders for sale
Pyrolysis liquid	Characteristic of the pyrolysis liquid: - initial boiling point ~75°C; - sulfur mass fraction <1%; - heat of combustion ~39 MJ/kg [10]	Raw materials for processing at refineries to produce petrol, diesel fuel and fuel oil, as well as sales of the product as heating oil

The table has been compiled by the authors.

The project success criteria are the following: project implementation period; sustainability of the project; project budget; reaching the established production capacity; production capacity increase.

The project of construction of waste tire processing plant based on project management methodology which helps to plan and control the project stages in a timely manner, interact with key stakeholders and get their support, effectively achieve the project goals. And besides, it will lead to the sustainable development of the region.

For the successful implementation of the project, the authors proposed dividing the project life cycle (PLC) into following phases: initiation, project development, construction and operation. Each phase has its own project activities and a hierarchical structure of the project activities in the form of a “Project tree”. At the end of each phase, project control points are highlighted [19].

At each phase of the project the authors have considered specific risks and suggested how to prevent them. The highest risks are expected to appear during the construction and operation phases in solving financial and production issues. Project risks of 15% are taken into account when determining the discount rate.

A project team should include competent specialists assigned all project schedule activities. The project team consists of the project coordinator engineer, project technologist, construction manager, purchasing and supply manager, contract manager and operational test coordinator. Project team members are subject to special requirements. All of them should be highly qualified team workers and understand the specifics of project activities. They also should be able to work under pressure and be ready for unusual situations in order to quickly respond to changes [19].

To implement the project, it is necessary to buy the equipment; the production capacity of the pyrolysis plant will amount to 3.6 tons per day. The total investment for construction waste tire recycling plant amounts to 8.3 million rubles (table 5).

Table 5. Project investment structure.

Investment	Amount, thous. rub	Structure, %
Purchase and installation of equipment	4 200	51
Building and construction	2600	31
Marketing costs	500	6
Working capital	1 000	12
Total	8 300	100

The table has been compiled by the authors.

The production plan of the project is based on the output of finished products per day, which are following: liquid fuel – up to 1.3 t, carbon black – up to 1.6 t, metal cord – up to 0.4 t, gas – up to 0.4 t. The project implementation period is 5 years. To calculate the volume of sales in value terms, the authors have taken market prices (May 2019), (table 6).

Table 6. Production plan of the project.

Years of project operations	1	2	3	4	5	Total
Capacity utilization, %	50	80	100	100	100	–
Pyrolysis fuel, t	117	187	234	234	234	1 006
Carbon black, t	144	230.4	288	288	288	1 238
Scrap, t	36	57	72	72	72	309
Pyrolysis fuel, thous. rub	2574	4 118.4	5 148	5 148	5 148	22 136.4
Carbon black, thous. rub	7 920	12 672	15 840	15 840	15 840	68 112
Scrap, thous. rub	216	345.6	432	432	432	1 857.6
Total, thous. rub	10 710	17 136	21 420	21 420	21420	92 106

The table has been compiled by the authors.

Further on, the researchers carried out feasibility study of the waste tire recycling project. Key indicators of economic efficiency of the project were calculated at a discount rate of 30%, which is shown in Table. 7. The analysis of the indicators of economic efficiency of the project proves that the project of the construction of the plant for the processing waste tires with the help of pyrolysis is profitable and appropriate for implementation.

To estimate the environmental and economic efficiency of the project, we use the indicator of the overall environmental and economic efficiency, which is defined as the ratio of environmental and economic benefit of the environmental protection measures to the totality of all additional costs incurred for its implementation.

Table 7. Key indicators of economic efficiency of the project.

№	Name of the Indicator	Unit	Rated Value
1	Net income	thous. rub	26 304
2	Net present value	thous. rub.	2 841
3	Discounted payback period	years	4.5
4	Index of profitability investment	−	1.34
5	Internal return rate	%	56.0
6	Return on investment	%	114.0

The table has been compiled by the authors.

When recycling used tires, the results are made up of a combination of economic and environmental effects. The economic benefits are determined when calculating the economic efficiency of the project. The environmental benefit consists of the amount of the environmental fee paid by the tire manufacturing company and the amount of damage caused to the soil prevented. The calculation results are given in Table 8.

Table 8. Calculation of the environmental and economic efficiency.

№	Name of the Indicator	Rated Value
1	Damage caused to the soil by unauthorized waste disposal, thous. rub.	308 880
2	Environmental fee, thous. rub.	89 930
3	Economic benefits, thous. rub.	27 805
4	Environmental benefits, thous. rub.	398 810
5	Environmental and economic benefit, thous. rub.	426 615
6	Overall environmental and economic efficiency, rub./rub.	51.4

The table has been compiled by the authors.

The main environmental benefit of the project is the recycling of accumulated and newly generated waste. It helps to prevent the accumulated environmental damage and prevent damage to the environment.

5. Conclusion

The key to the transition to a circular economy is the creation and implementation of a waste management strategy, as well as the promotion of recycling and usage of recyclable materials.

Waste tires are non-biodegradable, so they lead to long-term environmental pollution. The problem of waste tire recycling have remained relevant for many years.

Recycling of waste tires and rubber products is of high ecological and economic importance for all countries of the world. It is necessary to recycle and reuse waste with maximum efficiency because of the irreplaceability of natural capital.

Used tires, cameras and other rubber products are the finished goods to be disposed of after they have lost their consumer properties. Manufacturers and importers are required to pay an environmental fee if they do not comply with the recycling standards.

Nowadays, there are not enough tire processing plants in the Russian Federation, and the percentage of recycling of rubber products does not exceed 17%.

The authors have suggested the project of the construction of the plant for the processing waste tires with the help of pyrolysis which is profitable and appropriate for implementation.

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