On the Issue of Developing Integrated Plastic Recycling Units

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1 Introduction

Packing goods is a useful decision for both storage and transportation. The market for packaging materials was divided between such goods as carton/paper, glass, and metals just 50 years ago [1]. Those are still usable with certain inconveniences: full glass bottle of wine weighs 60% more than the wine by itself [2], carton and paper packs cannot be used for wet materials, and metal barrels are expensive. Invention of plastic packs had rapidly conquered the mind of customers because of their cheapness, suitability, light weight, and aesthetic view. It turns into various shapes, guarantees long life, provides good resistance and isolation. Furthermore, its success was inspired by the need for resource-saving solutions [3].

However, it forms a new culture of pack detailing: for example, tea is put in a plastic mesh or filter bag, and then packed in the foil sachet; afterwards a couple of sachets are put into a carton bag; then carton bag is packed once again into the plastic tape. It leads to the fact that the pack weight can be larger than the weight of the packed product [4]. Marketing policy aims at reducing the quantity of packed material in order to give a minimal price for unit, though sometimes every apple (pepper, slice of cheese, chocolate sweet, etc.) is packed separately [5]. Every pallet is tightened with a thick layer of polyethylene tapes. Finally, every pack is colored brightly to be attractive.

Opportunities to discover new plastic materials makes them suitable in various of components in cars, planes, industrial and domestic equipment, while replacing recently used materials partially or entirely. This entire amount is thrown away after

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Table 1 The structure of generated municipal solid waste in Russia

Component	Share, %	Weight, million tons per year
Paper and carton	36–42	17.6–20.6
Food	25–37	12.3–18.1
Metals	3–6	1.5–3.0
Textile	3–6	1.5–3.0
Wood	1–5	0.5–2.5
Glass	3–6	1.5–3.0
Stones	1.5–3	0.7–1.5
Leather and rubber	1.5–3	0.7–1.5
Plastics	5–6	2.5–3.0

the end of the usage term. Plastic garbage has a little origin in industrial processes, mainly it comes from municipal solid waste (hereinafter—MSW), which is generated at an average national level of 49 million tons per year [6].

In Russia, the National Strategy of Waste Management [7] defines the share of MSW components as shown in Table 1.

The national rate of MSW utilization does not exceed 8% [8]; meanwhile in some stores, it reaches 80% for plastic pack garbage [9]: this means that annually, more than 2 million tons of plastics are "lost" at Russian landfills or somewhere in the natural environment. More than 7 billion tons of plastic waste were already disposed in the environment during the plastic industrial manufacturing era globally [10]. For many years it had come to the Asian countries, but since 2018 China and its successors had banned the adoption of most kinds of plastic garbage [11].

Due to the ability of polymers to keep their properties during recycling, this business has numerous opportunities with regard to the circular economy: sometimes the recycled plastic can entirely substitute the original material, or can be used as an additive to it with the sufficient share. Plastic recycling helps improving the resource efficiency by reducing the consumption of oil and other natural resources (energy, water, etc.). Every dollar invested in recycling can save up to 7 dollars expenses in oil mining; and every pound of a recycled plastic can save half a gallon of oil [12].

An average price of recycled plastics is at least 40–50% lower than the original material, and this is why one can save millions of dollars every year by using recycled materials for manufacturing goods [13].

MSW flows originated from different regions have rather similar structures; moreover, composition of plastics present in MSW is relatively stable; finally, the economic feasibility of MSW transportation is limited. These factors suggest that it is reasonable developing a network of integrated plastic recycling facilities, which cover a selected territory and the gross amount of garbage. In this article, we describe key approaches of forming such a network.

2 Plastic Recycling Techniques

In general, plastic recycling means restoring properties of original materials and thereby making them suitable for manufacturing industrial goods. It is achieved by a number of thermomechanical methods of processing, including sorting, shredding, agglomerating, and extrusion. This treatment aims at maximizing the homogeneity of composition and stability of properties of the recycled material, allowing it to be added to a primary raw material in a proportion, which depends on consumer requirements (see Fig. 1).

Share of recycled plastic varies from 12 to 15%, this amount is possible to add into most manufacturing processes except some goods for children and medicinal items, to 100% for some kinds of garbage bags and solid construction filling materials [14].

Extrusion process needs the specified fluidity of the heated and melted plastic mass. However, thermal treatment should be carried out at temperatures above 190–230 °C for low- (hereinafter—LDPE) and high-density (hereinafter—HDPE) polyethylene agglomerate and up to 350 °C for polyethylene terephthalate (hereinafter—PET) flex, which leads to destruction and shortening of monomer chains and worsens the recycled material quality [15]. Therefore, the so-called repeatability limit of recycling of polymers is limited to 5–10 times, while metals or glass have much longer potential of utilization [16].

One of the most significant technical properties of plastics (as raw materials) is a so-called melt yield strength, because it effects formation of the extruded stripe or string. Keeping this property in the narrow range is difficult, especially when

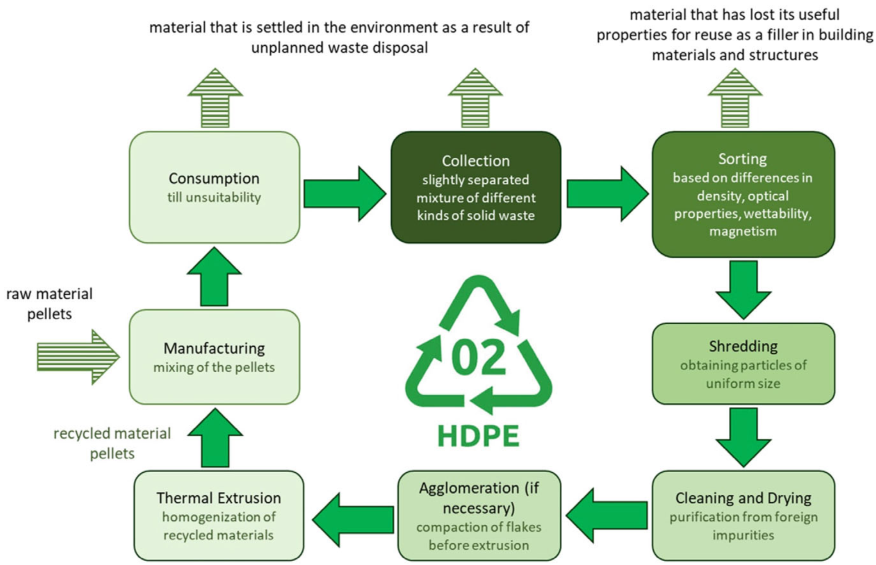

Fig. 1 Main stages of the plastic recycling process (drawn for HDPE as an example)

one deals with a mixture of different materials not separated by customers. Even small (3–5%) inclusions of one "unwilled" polymer can change the properties of the material [17].

For example, the presence of polypropylene (PP) in manufacturing HDPE goods increases the brittleness of the product and sharply reduces its photochemical resistance. The presence of HDPE in manufacturing LDPE films worsens the elasticity and cracking resistance of the product.

This problem can be partially solved by the careful multi-stage waste sorting, which should be started by people who separate waste at home. Initial separation varies from country to country and reaches nearly 35–40% in North America and 60–70% in the Netherlands and Scandinavian countries, South Korea, and Japan [18]. Only 8–10% of MSW is initially separated in Russia [19], but its share in 2024 was almost doubled in comparison with 2013 [7].

Specialized organizations—garbage collectors—acting as suppliers for the recycling enterprises play a rather important role in the "fate" of recycled plastics. Collectors press garbage to decrease its volume (up to 10 times), which makes the overall logistics possible. Economic calculations justify that collection area of pressed plastic garbage can reach 250 km in diameter [20].

At the next stage (at special stores), the separation rate can be raised up to 90–95% with the help of mechanics and the skills of the sorting workers [21]. This means that every material is selected properly according to its type to be further processed.

Currently, analytical methods used to separate various plastics are based on the spectral response in the infrared range. Unfortunately, this is too expensive for most waste management units; an alternative approach applies Artificial Intelligence (hereinafter—AI) techniques [22]. Waste is recognized by its appearance and is compared to a huge database of examples automatically. AI techniques provide for the quality similar to the manual sorting without large investments in specific equipment.

After sorting, plastics should be put into the washing machine to evacuate majority of impurities such as metal, glue, and labels. Their absence is essential for producing blow films, because even a small particle can damage a blowing sleeve. This process radically improves the raw material quality.

Washed plastic is put by numerous conveyor belts to a shredder, which (1) tears big particles into flakes, (2) makes them homogeneous, and ready for the further agglomeration (if necessary). Small particles are packed tightly, which makes it easier to heat them during extrusion. In order to make particles greater and to increase the flakes' density (up to 5 times), steam agglomeration is applied. Using agglomerated particles helps improving stability of extrusion machines by a smoother heating.

Sorting shredded waste is impossible. Prohibiting the unconditional use of multilayer materials (especially in single-use packaging), coupled with the limitations to the combine application of difficult-to-recycle materials with easily recyclable ones, can significantly improve the quality and ultimately increase the share of recycling.

Agglomerated flakes are melted in order to homogenize the substance. Liquid plastic mass is passed through forming molds, and then chilled and cut to one-size pellets. These pellets become a recycled additive or main raw material for manufacturing final goods at various chemical enterprises. It should be emphasized that

1 ton of pellets occupies a volume which is in 3–4 times less, than that of initially pressed plastic garbage, and this is why the economically feasible range of their transportation can been raised up to 800–1000 km.

Implementation of new technological processes allows using plastics additive fillers to a large group of materials such as construction materials (concretes), rubber, etc. [23], which significantly widens opportunities for plastic recycling.

There are chemical methods as well; one of them is based on pyrolysis (pyrolytic destruction) of polymer chains to monomer molecules that can be used as raw materials in organic synthesis [24]. This chemical technology cannot help to obtain a material with properties similar to the original one and would become the basic for hard-to-separate mixtures. Main difficulties of its application relate to the low prevalence of pyrolysis facilities and their disconnection from chemical installations. Polycondensation is an alternative; during this process, initially divided monomers unite again to form a polymer similar to the recycled original.

In vast areas with low population, plastic recycling may be unprofitable. In these cases, it is advisable using plastic waste as a fuel [25]. There are life cycle assessment methods that can quantitatively describe parameters, which can help select the proper plastic utilization way. The most frequently used approach is a waste material flow analysis, which includes the visualization of the origin, flow and consumption of some types of recyclable materials.

In Europe, to substantiate decision-making in the field of waste recycling, several geographical information systems have been developed. In Russia, according to the national legislation, territorial schemes of waste flows should be evaluated in every region. There are some attempts to develop global flow models for specified metals (particularly used in electronics), plastics, glass, etc. Even a brief analysis of material flows and their comparison with the National statistical report forms shows that the great body of plastics is lost in mixed MSW. In fact, plastics often are applied just once, and then they buried in the landfills or burned to generate heat (at the best).

Along with the waste material flow analysis method, the level of accumulated exergy (Cumulative Exergy Demand, also known as Cumulative Exergy Consumption, hereinafter—CExD) is used as an indicator of the system. CExD is introduced to designate the sum of exergies for all resources required to produce a certain product. CExD evaluates the quality of energy demand and includes the exergy of energy carriers, as well as non-energy materials [26]. Lower CExD suggests a better opportunity for secondary resource because it will not add many exergies to the final product, and the recycling exergy efficiency will be higher. This solution linking together the "cradle to grave" to the "grave to cradle" concepts, is recommended to evaluate the Exergy Replacement Cost (ERC) and identify the energy efficiency within the structure of the total resource efficiency [27].

Many countries consider opportunities for using 5–25% of recycled plastics in the goods contacting with food, and this proportion increases following deeper cleaning of the raw material [28]. Applying extruders with double-head molds makes it possible using recycled materials for the outer part of preform, while original raw material is used for the inner surface contacting with food.

3 The Integrated Plastic Recycling Unit

Knowing composition of the plastic garbage allows making right decisions in terms of selecting recycling equipment. Table 2 shows the typical composition of plastic waste for Canada. Considering similar consumption standards, climate and infrastructure, one can expect a similar structure of plastic waste for Russia.

Due to a short range of profitable logistics, the desired recycling enterprise should cover all components of plastic garbage. Average person produces about 300 kg of MSW annually [30]. Table 3 shows the difference of the garbage generation rate in different regions and communities.

One can see that even for rural areas, a small recycling enterprise (with capacity of 1,000 tons per year) is desirable. According to the share shown in Table 2, we can determine the specific capacity for every type of plastic. Numerous proper quality goods can be can be manufactured with the sufficient share of recycled material:

Table 2 The structure of plastic garbage in Canada [29] and estimated mass in Russia

Component	Share, %	Estimated mass in Russia (2 million tons equals to 100%), tons per year
Low-density polyethylene (LDPE)	30	600,000
High-density polyethylene (HDPE)	10	200,000
Polyethylene terephthalate (PET)	35	700,000
Polypropylene (PP)	10	200,000
Polyvinyl chloride (PVC)	4	80,000
Acrylic-butadiene-styrene (ABS)	7	140,000
Polyamide (PA)	2	40,000
Others	2	40,000

Table 3 The annual garbage generation in different regions (circle with 100 km radius) with the same level of consumption

Territory	Human population density per km^2	Generated garbage, kg	Plastic garbage, kg
Arctic regions	1	2,355	118
Rural area	12	28,260	1,413
European part of Russia	23	54,300	2,714
Urban area	200	471,000	23,600
Highly urbanized area	2,000	4,715,000	236,000
Megapolis	5,000	11,820,000	590,000

- for PET—3D printer's filament, synthetic fabrics, waste and various baskets, PET bottle preforms, lawn tiles, polymer-concrete, and construction materials;
- for HDPE/LDPE, PP—plastic fencing mesh, sewage and drainage pipelines, corrugated isolation pipes, curb tapes, waste bags, plastic cans, baskets, boxes, floorings, wood-plastic compounds for decking boards, and construction materials;
- for ABS—3D printer's filament, containers, car bumpers, and any kind of plastic reinforcement details;
- for PVC—wood-plastic compounds for decking boards, furniture, and construction.

Based on the performance of widespread plastic processing equipment (100–250 kg per hour), capacity for 1-shift recycling workshop can be assessed as 1000-ton per year. Such workshops may include the following equipment lines (as an example):

- HDPE Plastic Rigid Net and Geonet Machine;
- HDPE/LDPE Square Mesh Production Line;
- LDPE Single Wall Corrugated Pipe Machine;
- PET Strap Production Line;
- LDPE/HDPE Film Blowing Machine;
- Drum Type Cutting off On-roll Bag Making Machine;
- Servo Energy Plastic Injection Molding Machine;
- Injection Blow Molding Machine;
- LDPE/HDPE Film Washing Line;
- HDPE/LDPE/PP Extrusion and Granulation Line;
- PET Bottle Washing Line;
- Granulating Line for PET Bottle Flakes;
- Industrial Shredder foe Plastics;
- PET Monofilament Extruding Line.

The following goods can be produced annually at the unit with the 15–100% share of recycled plastic:

- Plastic mesh and Geonet—350 tons;
- Waste bags—250 tons;
- Various plastic details—250 tons;
- Corrugated isolation and drainage pipes—150 tons;
- Strap tape and 3D printer filament—150 tons;
- Plastic filler as a construction material—350 tons.

Plastic filler is the "final fate" of plastic because it accumulates materials of worst quality, not applicable for manufacturing goods.

There are some plastics that have little potential for such kind of utilization: polystyrene (especially foamed), and polyvinyl chloride. The latter is essential for Wood-Plast Composite manufacturing. In most cases, polystyrene and polyvinyl chloride are incinerated, despite harmful emissions (to be combated), because there is a little number of recycling facilities that can operate with these plastics.

Geographical combination of integrated plastic recycling units, with a singular working staff of 35–40 people can cover a vast territory with low population density; alternatively, integrated plastic recycling units can be concentrated in urban areas. Development of a plastic recycling enterprise should be divided into several steps. Every next step would adjust the manufacturing. It depends on marketing investigation, business plan corrections, and considering different technologies. Of course, the final product has to find its place on the market, and a cheaper price improves opportunities for expanding both manufacturing and sales.

4 Conclusion

The main environmental idea of recycling is to prolong the life cycle of a product and significantly reduce negative environmental impacts at every stage of manufacturing. Enormous amounts of various emissions originating from oil drilling, refinery, plastic production, and logistics can be entirely prevented by using recycled materials.

Well-planned establishment of integrated plastic waste recycling points, incorporated into the territorial schemes of various regions, will provide for setting up a recycling network based not on the availability of equipment, but on the demographic factors. This solution will allow to significantly increase the degree of plastic recycling (and using plastics as secondary resources).

Circular economy should be based on a combination of market and planning principles with national and local governments implementing appropriate measures to stimulate consumption of recycled resources.

Recycling as an industrial process has very few emissions by itself; certainly, there should be special environmental procedures and equipment on this stage, especially when processing medical waste, polyvinyl chloride, and polyethylene terephthalate. In most cases, such processes emit aerosols of melted plastics that can be easily caught by standard filters.

Researchers claim that small amounts of the residue are detected in water after washing (up to 0.005% of the recycled material mass) [31]. Water is fully recycled. Biological and other hazardous waste should be treated separately (preferably—incinerated). No solid waste is produced because plastic is returned into recycling at every stage. Heat formed during the process is used to heat the workshop during cold seasons, which means that energy loss is very little.

Thus, forming a network of integrated plastic recycling units provides for nearly full MSW management coverage. This solution contributes towards the implementation of the Sustainable Development Goals focusing both on environmental, social, and economic aspects.

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