Nova paradigma u recikliranju - inovativni pristup recikliranju plastičnog otpada u Srbiji

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Apstrakt: Ključni problemi recikliranja plastičnog otpada u Srbiji su neadekvatna zakonska regulativa i niska otkupna cena otpadne plastike koja ne predstavlja podsticaj za njeno sakupljanje u većoj meri. Ovaj rad predlaže metod za recikliranje plastike koji se bazira na pirolitičkoj konverziji plastičnog otpada u supstitute goriva kao primarni način reciklaže. Metod se ogleda u više različitih smernica za njegovu primenu. One su detaljno objašnjene i prikazane u ovom radu. Ukoliko bi zakonodavac prepoznao ovaj metod recikliranja kao društveno odgovorno poslovanje i uneo određene izmene u zakonskoj regulativi, i ukoliko bi navedene smernice bile ispoštovane, implementacijom ovog metoda mogao bi se stvoriti prostor za veću otkupnu cenu plastičnog otpada. Ekonomski posmatrano, viša cena otkupa povećala bi ponudu, odnosno podstakla sakupljanje plastičnog otpada u većoj meri što bi imalo pozitivan ekološki efekat uz ekonomsku opravdanost.

Ključne reči: Recikliranje plastike, piroliza, zamena za dizel, ekološki.

A New Recycling Paradigm - an Innovative Approach to the Plastic Waste Recycling in Serbia

Abstract: The key problems of plastic recycling in Serbia are inadequate legislation and low purchase price of plastic waste, which is a poor incentive for plastic waste collecting. This paper suggests the method for plastic waste handling in Serbia by means of pyrolytic conversion into fuel substitutes as primary recycling method. It is reflected in several guidelines for its application, which are explained in detail, proved and given in this paper. If the state recognized this method as a socially responsible business by introducing certain legal regulation changes and if the above guidelines were followed, the implementation model could make a room for a higher purchase price of plastic waste. In economic terms, higher price would increase supply by encouraging the collection of plastic waste to greater extent, which would have a stronger environmental impact with economic justification.

Keywords: Plastic recycling, pyrolysis, diesel supstitute, ecological.

1. Introduction

Assessment of plastic flows and stocks in Serbia using material flow analysis revealed that approximately 269,000 tons of plastic materials *per annum* were directly disposed in uncontrolled landfills on its territory without any pretreatment (Vujic, Jovicic, Babic *et al.*, 2010). Prokic and Mihajlov (2012) also concluded that the waste management in Serbia is inadequate. Environmental and health concerns are integral part of this problem. The national goal in the management of packaging waste, set by the regulation on the establishment of the packaging reduction plan for the period from 2015 to 2019 ("*Uredba o planu smanjenja ambalažnog otpada za period od 2015. do 2019. godine*", "*Sl. glasnik RS*" no. 144/2014), amount 22.5% of recycled plastics waste (PW) per year. The Association of Recyclers of Serbia has repeatedly expressed concern, through public media, about the low level of plastic waste recycling. They repeatedly appealed to the state to introduce some changes towards recycling regulations and stated that they use only 30% of their recycling capacity. There are multiple reasons for this. The main reason lies in the plastic recycling method itself. Plastics waste management can be subdivided into three following hierarchical sequence (Buekens and Schoeters, 1998):

1. mechanical or materials recycling, preserving the macromolecular structure of plastics polymers;

2. chemical or feedstock recycling, converting plastics into monomers or petrochemical feedstock, and
3. energy recycling, such as in the incineration with heat recovery of plastics contained in municipal solid waste.

The first one, which is most commonly used method in Serbia, consists of the following steps: collecting, sorting, grinding/shredding, floating, contaminant separation, milling, washing and drying, chemical washing, melting and pelletizing plastic materials. It is obvious that a serious approach to the preparation and processing of PW is necessary since the final recycling product must be consisted of exactly one type of plastic with no impurities because it is later used for the further manufacture of plastic products. In addition, the obtained product has a lower quality than the starting material and can't be used to produce all range of plastic products. The initial investment, complexity of the process and a relatively low price of non-recycled, new plastic dictate the low purchase price of PW in order for the recycling plant to profit. Furthermore, waste disposal system in Serbia, in the greatest extent, does not include sorting of waste. All municipal waste goes to common dumpsters and is disposed on same landfills. This means that recycling companies are forced to buy much of their raw material from groups and individuals who earn their living by collecting and sorting waste (SECOL). This is obviously a huge drawback of the recycling process since those individuals stated that they have been rather choosing to collect paper and metal instead of plastics due to the low PW purchase price. Through market research, which consisted of contacting 25 recycling companies and numerous individuals from branch, it was established that the maximum price that could be obtained by SECOL for kilogram of well-prepared PW in Serbia amounts approximately € 0.25. The goal of this manuscript is to review and suggest a new approach to PW recycling in Serbia that would allow for a higher purchase price of PW and thus encouraged collection of PW in greater extent.

The method proposed by this paper is pyrolytic conversion of PW into fuel substitutes. It is regarded as a primary recycling process rather than plastic granules production. The definition of thermal pyrolysis given by Stauffer (2003), says that it is a process, by which a solid (or a liquid) undergoes degradation of its chemicals into smaller volatile molecules by means of temperature, usually between 350°C and 900°C, without interaction with oxygen or any other oxidants, that is necessary for almost all solids (or liquids) to burn. PW pyrolysis process consists of steps shown in the following scheme (Fig. 1):

Fig. 1 - Simplified scheme of the plastic and tire waste pyrolysis process

The process results in different products: liquid oil, gases, char, wax and additional residues that depended on what has been fed into the reactor (Miandad, Barakat, Aburizaiza *et al.*, 2016; Owusu *et al.*, 2018; Xingzhong, 2006; Sogancioglu, Ahmetli and Yel 2017; Demirbas, 2004). The liquid products from PW could be considered as a mixture of heavy naphtha, gasoline and light gas oil fractions (Demirbas, 2004; Owusu *et al.*, 2018). A large number of studies have been conducted on this subject and all indicated the use value of the products obtained by this route. The literary data supporting the goal will be presented. The review will consider which type of plastic waste is suitable for the pyrolysis, which process yield favorable results – continuous or batch, and where the potential application of the described method could be found.

Table 1. The list of acronyms and abbreviations

HDPE	High-density polyethylene	PS	Polystyrene
LDPE	Low-density polyethylene	PVC	Polyvinyl chloride
PE	Polyethylene	PW	Plastic waste
PET	Polyethylene terephthalate	SECOL	Secondary raw material collectors
PO	Plastic waste pyrolysis oil	WTPO	Waste tire pyrolysis oil
PP	Polypropylene		

2. Methods of collecting data and experimental set up

The data used in this study belong to the primary and secondary collection of data. For the purpose of an economic and feasibility analysis the current prices of energy products, raw materials, PW and equipment were needed. The market research was conducted based on direct contact with recycling companies, equipment manufacturers and individuals from the branch. Considering the presented paper, which aims to investigate and suggest an implementation model, the data relating to techno-economical aspects were obtained from the first-hand experience through the construction of pilot pyrolysis batch reactor (Fig. 2) that was carried out with the courtesy and efforts of Filip Dimov¹. The material used for the key elements of the reactor consisted of a: 220l tin barrel for the outer shell; a 50l liquid petrol gas tank used as a reactor; two large flanges allowing feeding of the reactor; 6kW iron-chromium-aluminum (FeCrAl) wire heaters – which were submerged into chamotte and wrapped around the reactor; an 0-800°C adjustable thermostat; ≈150 kg of chamotte powder; stone mineral wool; plastic and metal pipes and a mild vacuum pump.

Fig. 2 – Scheme of the constructed setup and pyrolysis batch reactor

The presented literature data was chosen referring to the goals of this manuscript, based on the process of pyrolytic transformation of plastic waste into fuel substitutes, rather than plastic granules production. They will be presented here as a primary recycling process that could supplement the existing recycling methods in Serbia. The review will consider what type of plastic waste is suitable for pyrolysis, which process gives better results - continuous or batch one and where the potential application of the product of pyrolysis, liquid pyrolysis oil, can be found.

3. Conversion of plastic waste into fuel substitutes by means of pyrolysis

3.1 Potential application of liquid pyrolysis oil

Mani, Subash and Nagarajan (2009) analyzed and compared properties of the oil derived from waste plastics with the petroleum products and found that it had properties similar to that of diesel. Some of their conclusions were that engine was able to run with 100% PO; ignition delay was longer by about

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2.5 CA in the case of PO compared to diesel; smoke was reduced by 40% at rated power in PO compared to diesel operation and that engine fueled with PO exhibited higher thermal efficiency up to 75% of the rated power. According to Owusu *et al.* (2018), the results of density, kinematic viscosity, dynamic viscosity, distillation range and calculated cetane index of PO were comparable with conventional transportation fuel. Miandad *et al.* (2016) also found that PO were similar to conventional diesel, thus had potential to be used as alternative energy source for electricity generation. However, presence of high aromatic compounds in liquid oil made it unsuitable as a transport fuel until it was upgraded using different post-treatment methods such as distillation, refining or blending with conventional diesel. The use of pyrolysis liquid oil as transport fuel has been successfully tested after blending with conventional diesel at different ratios (Demirbas, 2004; Islam *et al.*, 2010; Lee *et al.*, 2015) blended 20 and 40% of pyrolysis liquid oil with conventional diesel and concluded that at 20%, a successful engine running was achieved. Kaimal and Vijayabalan (2015) concluded that a 25% plastic oil–diesel blend could be considered as an effective replacement for diesel in compression ignition engines without any modifications. Furthermore, disposal of waste automotive tires, one of the most important problems hand in hand with plastic, could be solved by means of pyrolysis in the same manner as it was described for plastic waste (Islam *et al.*, 2010; Hürdoğan *et al.*, 2017; Vorkapic *et al.*, 2010). Hurdogan, Ozalp, Kara and Ozcanli (2016) found that the blends of waste tire pyrolysis oil (WTPO) could also be efficiently used in diesel engines without any engine modifications and that blend with 10% of WTPO in diesel could be the best alternative fuel blend for diesel engines, not only for its performance characteristics but also for the environmental aspects.

3.2 Plastic waste suitable for pyrolysis

Contrary to common plastic recycling, pyrolytic method has advantages in different areas (John Schiers, 2006):

- it does not require detailed sorting and costly and complex process of PW preparation (drying and milling of plastic is performed with the aim of maximizing the reactor yield);
- it allows the recycling of waste mixed plastics that cannot be efficiently recycled by common method;
- it permits the recycling of unwashed and soiled plastics (e.g. agricultural plastics, mulch/silage/greenhouse films and dripper/irrigation tube); and
- enables recycling of plastic laminates, co-extrusions and multilayer packaging films, particularly those with aluminum foil layers that are difficult to recycle using traditional reprocessing technologies.

Considering the manner of processing and the insensitivity of the system to possible minor impurities, pyrolysis method opens a possibility of gathering diverse types of PW suitable for the conversion: plastic cups, clothes hangers, park benches, flower pots, toys, tables, roadside curbs, benches, plastic bags, bottles, plugs, car bumpers etc. These are all products made from few common types of plastic given in the bar chart in the Fig. 3 (Sogancioglu, Ahmetli and Yel, 2017). The figure shows the liquid yield of several plastic materials depending on the temperature of the pyrolytic reaction. Samples fed to the reactor were not pre-washed. In the research, conducted by Owusu *et al.* (2018), it was shown that a degradation temperature of thermal pyrolysis from 300 °C to 450 °C, in a batch reactor resulted in the highest yield of liquid fractions. Before them, Muhammad, Onwudili Williams, P. T. (2015) also got similar experimental results with same conclusions. However, there are plastic materials that are not adequate for pyrolysis. Marco, Caballero, Torres *et al.* (2002) showed that PET pyrolysis is rather problematic as no liquids were obtained in the outlets of the autoclave¹. Only obtained product was yellowy powder, which stuck to the walls of the pipelines, making it impossible to collect and quantify the pyrolysis products. Such a product caused, in some cases, the obstruction of the installation, forcing the experiment to be stopped. It seemed that PET decomposed in pyrolysis generating terephthalic acid and/or similar products which sublime and condense to a solid when cooled. The research conducted by Sogancioglu, Ahmetli and Yel (2017) also showed that product obtained from PET was not a fluid. Instead, it was collected as soft, ductile form and therefore, there is no economic or other justification for pyrolysis of PET. Since the PET packaging is commonly recycled in Serbia to the greatest extent compared to other types of plastics, this shortage does not have to be seen as a disadvantage. It could be viewed as a point of conflict reduction between the usual recycling.

¹An *autoclave* is a pressure chamber used to carry out industrial processes requiring elevated temperature and pressure different from ambient air pressure.

Furthermore, PVC which is one of the most thermally unstable polymers, of which 58.5 wt % is chlorine (Menges and Berndtsen, 1977) generates different problems in the process of pyrolysis. It's been shown that hydrogen chloride (HCl) was generated in pyrolysis, when PVC was heated to about 300°C (Williams and Williams, 1997; Keane, 2007). Keane concluded that it is essential to remove Cl component from PVC-derived oil and that use of Cl-containing fuel oil would result in severe unit corrosion and the release of environmental toxins – conversion of waste PVC into fuel oil necessitates some form of dechlorination steps. That procedure would increase the cost of required equipment and the production of pyrolysis oil. Blazsó (2006) and Lin, Huang, Luo *et al.* (2010) also showed that pyrolysis of mixed PW containing PVC released hydrogen chloride which caused not only corrosion of the equipment, but also the formation of organochloride compounds in hydrocarbons. Wu *et al.* (2014) showed that the pyrolysis of PVC leads to the production of dioxins which are highly toxic environmental persistent organic pollutants (Berg *et al.*, 2006). Because the HCl may corrode equipment, deactivate catalysts and deteriorate the quality of products this manuscript recommends that PVC is removed from the pyrolysis mixture.

Fig. 3 – Pyrolysis liquid product yield in % depending on reaction temperature and type of plastic. The chart is based on experimental data obtained in the research conducted by Sogancioglu, Ahmetli and Yel (2017).

3.3 Continuous versus batch procedure

Continuous procedure implies uninterrupted flow of materials in production. Materials, which can be fluids or dry bulk, undergo chemical reactions or heat/mechanical treatment in continuous flow process contrary to the discontinuous batch process. In techno-economic analysis conducted in England (Fivga, Dimitriou, 2018), plant that uses continuous pyrolytic process with a capacity of 100 kg/h of plastic waste was modeled. Results showed that for the 1,000 kg/h case, the facility needed to operate approximately four years to recover the capital investment of nearly one million euro. Vorkapic, Ocic and Kurcubic (2006) proposed facility based on continuous procedure with initial investment estimated on €400,000. These were major investments which, in order to profit, implied constant PW supply required for maintaining the business continuity and thus large quantities of obtained product offered in the fuel market. This creates additional problems. To sell fuel, high excise taxes are obliged to be paid per liter of the PO as well as more complex preparation and strict quality management is necessary. The excise taxes on gas oil, liquid petroleum gas and bio-fuels in Serbia amounts ≈€0.48/l, ≈€0.36/l and ≈€0.47/l respectively (“*Sl. glasnik RS*” no. 18/2018). All this raises the final product price and reduces the profit area which brings us to the same stalemate position as in the case of conventional plastic recycling. On the other side, batch procedure had yields of oil fractions significantly higher than the continuous and at a lower pyrolysis temperature (Owusu *et al.* 2018). Other advantages are: smaller initial investments required compared to continuous procedure; conversion could be done *ad hoc*, when PW is available, without financial losses when that is not the case; conversion could be done *in situ* where PW is available in larger quantities; depending on the reactor type and configuration, one trained operator is sufficient for operating the reactor. Disadvantage of batch procedure would be small and finite capacity of PW processed per unit of time, compared to continuous reactor.

3.4 Equipment

3.4.1 Plastic grinders

Regarding the grinding/milling of PW prior to pyrolysis, twenty five grinders offered on the market were taken into account. Price of the adequate plastic grinder with the capacity of 200 kg of PW per hour was €1500.

3.4.2 Pyrolysis reactor

The market offers different varieties of equipment needed for PW pyrolysis. Prices of small, 50l batch reactors ranges from €3500 up to tens of thousands of euro. The price varies depending on capacity, heating type, material, technology, quality *etc.* Fig. 4 shows the experimental set up at Makerere University Agricultural Research Institute in Kabanyolo, Uganda that was used in the research conducted by Owusu *et al.* (2018). Thy pyrolysis was conducted in the batch reactor heated on burning wood. The purpose of this figure was to demonstrate that no hi-tech nor a large technologically demanding facility is needed for plastic pyrolysis to be carried out. It also shows that the process, depending on the settings, could be carried out *in situ* where PW would be available in larger quantities. The price of the reactor constructed as a part of this study (Fig. 1), which is described in the section 2, was approximately €580. Price of human labor, transport and welding materials were omitted because they vary greatly depending on the operational performance and production process design. Of course, if such reactor were offered on the market, its final price would be higher. However, its construction for the purpose of this paper has shown that a complete apparatus for the successful execution of the pyrolytic reaction can be produced with relatively small initial capital investment.

Fig. 4 – Batch reactor heated on burning wood (Owusu *et al.*, 2018)

3.6 Analysis of the pyrolysis oil production price

For the implementation of this process it would be necessary to know the production price of pyrolysis oil (PO). Taking into account the actual price of electricity and labor (*“Sl. glasnik RS”* no. 79/2017 and 88/2017 respectively), technical characteristics of the reactor and grinder as well as yields and time needed for the reaction, as well as other possible costs, the estimation of the PO production price was made possible through the following formulas. They were set for the purpose of paper:

$$ProdPrice = PyrPri + GrnPri + LbrPri + Other; \quad (1.1)$$

$$PyrPri = \frac{P_{price} \times t \times P \times H}{M}; \quad (1.2)$$

$$GrnPri = \frac{P_g}{C_g} \times P_{price}. \quad (1.3)$$

Table 2 - List of symbols used in the formulas

C_g – Grinder capacity $\left(\frac{kg}{h}\right)$	M – Amount of plastic fed into reactor (kg)
$GrnPri$ – Grinding price $\left(\frac{\epsilon}{kg}\right)$	P – Heating power of the reactor (kW)
H – Liquid fraction yield (%)	P_g – Grinder power (kW)
h – Hour	P_{price} – Electricity price $\left(\frac{\epsilon}{kWh}\right)$
kg – Kilogram	$ProdPrice$ – Production price $\left(\frac{\epsilon}{kg}\right)$
kW – Kilowatt	$PyrPri$ – Pyrolysis price $\left(\frac{\epsilon}{kg}\right)$
$LbrPri$ – Labor price $\left(\frac{\epsilon}{kg}\right)$	t – Time needed for the conversion (h)

Table 2. is shown here for easier formula tracking. The cost of PO production in the aforementioned reactor was taken as an example. The values used for calculation are explained as follows:

- Electricity price - “Higher daily tariff - red zone” price was used in calculation of the highest possible price of electrical energy in Serbia which amounts RSD 17.887 or $\approx \epsilon 0.1516$.
- Time - The literature available on this topic did not provide enough data that could be used for prediction of time needed for carrying out the pyrolytic transformation process to the end. Required time for the reaction depends on many factors, starting with temperature, quantity and type of plastics, reactor insulation, power of the heaters, adjustments *etc.* Papuga, Gvero and Vukic (2016) proposed a value of 90 minutes under temperature of 500°C for HDPE. However, due to a greater temperature they had a greater gaseous fraction yield which is not desirable in this case. In practice, it turned out that PE especially HDPE, in the first run came out as mostly paraffin like liquid that solidified at temperatures below 20°C. The resulting substance had to pass through the process one more time in order to reduce the thickening point and thereby acquire properties similar to the fuel. Based on all of the above, as well as the difficulty of accurately predicting the ratio of plastic masses in the material to be converted, the conclusion was made that the empirical practical experience in this case was to be relevant for the estimation of the required time. Based on the results obtained using the constructed reactor as well as the experience of different individuals involved in this process, four (4h) hour time was indicated as upper time limit for the completion of PW conversion, for reactors of a similar ratio of capacity and power, regardless the type of plastic fed into reactor and its occupancy rate.
- Heating power of the reactor - Constructed reactor had heating power of 6 kW. This means that when all the heaters are constantly switched on, 6 kW of electricity is consumed per hour. However, the automated thermostat switched off and again switched on the heaters at certain times, in order to maintain a constant temperature in the reactor. Nevertheless, the calculation used the value as if the heaters had worked all the time, because the upper limit of the price was calculated.
- Liquid fraction yield of the reactor – Oil yield depends on the mass ratio of the plastic types fed into the reactor. Data on percentage of plastic types produced (Plastic Europe, 2017), was used for estimation and approximation of the mass ratio of plastic types in the PW. The most common types of plastic were taken into account. The values of liquid yields are derived from experiments carried out by Sogancioglu, Ahmetli, and Yel (2017) in the batch reactor setting at low temperatures of 300-450°C. The average reactor liquid yield was estimated on 79.92%. The Table 3. and the formula 2.1 show how the estimation was made.

Table 3. Working table for calculation of average liquid yield

i	Type of plastic	x – Plastic type share (%)	f – Liquid yield by plastic type (%)	$x \cdot f$
1	PP	36,81	79,62	2930,81
2	LDPE	27,76	78,39	2176,11
3	HDPE	24,4	88,54	2160,38
4	PS	11,03	65,71	724,78
		$n=\Sigma x=100$		$\Sigma=7992.08$

$$\text{Average liquid fraction yield} = \frac{1}{n} \sum_{i=1}^4 x \cdot f \approx 79.92\% \quad (2.1)$$

- e) Amount of plastic fed into the reactor: Grinded plastic is relatively loose so it is impossible to fill the reactor up to 100% of its capacity. The plastic used for testing purposes was manually shredded and grinded. Approximately 28 kg of plastic material was fed into reactor. If the machine had been used for the grinding, plastic material would have been more compact and more of it would have been fed into the reactor. Therefore, this number of 28kg could be safely used for the calculation of the upper price limit.
- f) Grinder power: The values used for the calculation referred to a grinder with power of 7.5 kW that could be found on the market. The chosen grinder has capacity of 200 kg plastic per hour, which corresponds to figure g). In other words, 200 kg of plastic could be grinded with 7.5 kW of electricity consumed.

When these values were put into the formulas, the final estimation of pyrolysis, grinding and pyrolysis oil production price was made. The values are shown below in the Table 4:

Table 4 – Estimated values of pyrolysis, grinding and pyrolysis oil production price

Pyrolysis price	$0.104 \frac{\text{€}}{\text{kg}}$
Grinding price	$0.0057 \frac{\text{€}}{\text{kg}}$
Pyrolysis oil production price	$0.11 \frac{\text{€}}{\text{kg}} + (\text{labor and other costs})$

The pyrolysis and grinding costs for one kilogram of PO were estimated on 0.11€. The price of labor and other costs would increase this value but were deliberately omitted from the calculation and placed as separate factors because they vary greatly depending on the operational performance and production process design. In some cases, the price of labor could be reduced to almost zero. It is left to be estimated by the parties interested in the implementation of the proposed model of plastic waste recycling.

Further costs reduction could be achieved if the process was conducted by night, during the cheap tariff time or by using diesel aggregates running on the resulting oil for making electricity. In addition, if the reactor was designed to be heated by a burner, the gas fraction obtained in the pyrolysis process as well as the part of the liquid fraction could be used. It would be possible to reduce or completely eliminate dependence on electricity. This would reduce the yield of the end product, but at the same time it would reduce the cost of production and enable *in situ* conversion of PW into fuel substitutes in areas where no electrical energy is available.

4. Discussion

It was shown that the PW pyrolysis process, when conducted in the described manner, in a small batch reactor setup, required low initial capital investment and could be implemented anywhere across a wide territory. This means that more companies, entrepreneurs and individuals would be able to enter this business. Fuel substitutes obtained through the process could be mixed with automotive fuel or used as a fuel for heating objects as well as for other purposes, which together makes a great use value. If obtained PO were not offered on the fuel market, but instead, used as fuel supplementation by its manufacturers, excise taxes could be avoided as well as the complex and strict product quality management, which would otherwise be necessary if obtained product was to be offered on the fuel

market. The assumption is that the ideal users of the proposed method would be transportation companies, bus carriers, farm households, taxi associations, facilities and buildings that are heated on oil *etc.* It assumed that they would have the capabilities to procure the equipment and start implementing the process as an additional activity. In the same time, they would have sufficient fuel demand. If that was the case, savings in fuel purchases generated as a result of the differences in the price of diesel fuel and the PO that they produced should be regarded as a profit. PW used in the process is to be purchased and obtained from SECOL or directly from citizens. If the PW procurement were to grow, producers could continue to work on their capabilities regarding the process and increasing their capacity. The lowest end price of any diesel fuel on the Serbian market is 1.2€/l and the average price of diesel fuel used by automobiles is 1.37€/l. The high price of diesel fuel that PO substitutes and the relatively low production price of PO, estimated on 0.11€/kg provide a far greater financial space that is to be divided on saving and a larger purchase price of PW (Fig. 5). In economic terms, larger purchase price of PW would act as an incentive for numerous stakeholders. SECOL would be expected to start collecting PW to a greater extent. Citizens would also be expected to start sorting and selling their PW voluntarily, instead of just dumping it. Generally, far more entities would be expected to get involved in this activity and therefore, it could be potentially a milestone in solving the PW problem in Serbia.

Fig. 5 - pyrolysis + grinding compared to diesel fuel price

However, the major concerns regarding the recommended PW handling method are of a legal nature. In the year 2017, the state started to apply the decree on the marking of oil derivatives (*“Uredba o obeležavanju (markiranju) derivata nafte”*, *“Sl. glasnik RS”* no. 51/2015 and 5/2017). This allowed the market inspection to check the levels of markers in fuel that was taken from vehicles or agricultural machinery tanks. If low levels of markers were found, huge fines were imposed. The reason behind this was the state effort to control the black market and the gray economy. At the same time, problems emerged in the use of bio-fuels. This had a particular negative impact on farmers who have had the opportunity to produce bio fuels for their own needs, by which, they could have strengthen their own business while preserving the environment. Because of the excise tax on fuel, the state prevented different forms of socially responsible business that were in line with the global trend and efforts to encourage sustainable and ecological business. This could be changed if the state recognized these fuel production methods as a form of ecological end socially responsible business. A potential solution to the problem could be a model that would allow the marking of eco-fuels produced in the mentioned ways, by the authorized institutions. This would differentiate the produced eco-fuel from the contraband fuel. At the same time, it would allow control and insight into the quantities of produced eco-fuels. It would be highly recommendable if Serbia, as a legislator, supported and encouraged PW or bio-fuel production because it is in line with the national strategy and aspirations to preserve the environment and enable a better living standards.

5. Conclusion and recommendations

In order to avoid detrimental environmental consequences, a different approach to plastic recycling is obviously indispensable. Common PW recycling in Serbia did not show expected results and changes are necessary. This paper examined and reviewed different approaches of PW handling and proposed an innovative one, applicable in Serbia. It is reflected in the following guidelines:

- The conversion process is to be carried out by small producers as an additional activity and as a form of socially responsible business. Their primary business should

include the consumption of diesel fuel (transportation companies, bus carriers, farm households, facilities heating on diesel, taxi associations etc.).

- Pyrolysis is to be conducted in small batch reactors instead of a continuous one at the industrial level; small initial capital investment means that more entities would be able to get involved in the process.
- The obtained pyrolysis oil is not to be offered on the fuel market - instead, it is to be used as a fuel supplementation by its manufactures. This could eliminate the excise tax and the necessity for detailed PO quality management, and thus could make a room for a higher PW purchase price.
- It would be necessary that the legislator (the state) recognize this method as a socially responsible business and introduce certain changes to existing regulations.

Estimations of equipment and production prices were made to help in creation of implementation model. If the model adhered to these guidelines and state recognized it, it would have the potential to become a game changer in PW handling in Serbia. In the forthcoming period, a statistical survey on PW purchase price should be carried out. The survey should serve to determine which PW purchase price would satisfy SECOL. This manuscript sees their motivation as the key to the PW recycling success because they make the largest part of the scrap plastic supply chain. Therefore, the price is of a great importance as it represents the pivot point between the success and failure in further application of these methods.

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7. References

1. Almeida, D., & Marques, M. D. (2016). Thermal and catalytic pyrolysis of plastic waste. *Polímeros*, 26(1), 44-51. doi:10.1590/0104-1428.2100
2. Berg, M. V., Birnbaum, L. S., Denison, M., Vito, M. D., Farland, W., Feeley, M., . . . Peterson, R. E. (2006). The 2005 World Health Organization Reevaluation of Human and Mammalian Toxic Equivalency Factors for Dioxins and Dioxin-Like Compounds. *Toxicological Sciences*, 93(2), 223-241. doi:10.1093/toxsci/kfl055
3. Blazsó, M. (2006). Composition of Liquid Fuels Derived from the Pyrolysis of Plastics. *Feedstock Recycling and Pyrolysis of Waste Plastics*, 315-344. doi:10.1002/0470021543.ch12
4. Buekens, A. G., & Schoeters, J. G. (1998). Technical methods in plastics pyrolysis. *Macromolecular Symposia*, 135(1), 63-81. doi:10.1002/masy.19981350110
5. Demirbas, A. (2004). Pyrolysis of municipal plastic wastes for recovery of gasoline-range hydrocarbons. *Journal of Analytical and Applied Pyrolysis*. doi:10.1016/s0165-2370(04)00029-4
6. Donaj, P. J., Kaminsky, W., Buzeto, F., & Yang, W. (2012). Pyrolysis of polyolefins for increasing the yield of monomers' recovery. *Waste Management*, 32(5), 840-846. doi:10.1016/j.wasman.2011.10.009
7. Fivga, A., & Dimitriou, I. (2018). Pyrolysis of plastic waste for production of heavy fuel substitute: A techno-economic assessment. *Energy*, 149, 865-874. doi:10.1016/j.energy.2018.02.094
8. Hürdoğan, E., Ozalp, C., Kara, O., & Ozcanli, M. (2017). Experimental investigation on performance and emission characteristics of waste tire pyrolysis oil–diesel blends in a diesel engine. *International Journal of Hydrogen Energy*, 42(36), 23373-23378. doi:10.1016/j.ijhydene.2016.12.126
9. Ilić, M., & Nikolić, M. (2016). Waste management benchmarking: A case study of Serbia. *Habitat International*, 53, 453-460. doi:10.1016/j.habitatint.2015.12.022
10. Islam, M. R., Parveen, M., Haniu, H., & Sarker, M. R. (2010). Innovation in Pyrolysis Technology for Management of Scrap Tire: A Solution of Energy and Environment. *International Journal of Environmental Science and Development*, 89-96. doi:10.7763/ijesd.2010.v1.18

11. Kaimal, V. K., & Vijayabalan, P. (2015). A detailed study of combustion characteristics of a DI diesel engine using waste plastic oil and its blends. *Energy Conversion and Management*, 105, 951-956. doi:10.1016/j.enconman.2015.08.043
12. Keane, M. A. (2007). Catalytic conversion of waste plastics: Focus on waste PVC. *Journal of Chemical Technology & Biotechnology*, 82(9), 787-795. doi:10.1002/jctb.1757
13. Lee, S., Yoshida, K., & Yoshikawa, K. (2015). Application of Waste Plastic Pyrolysis Oil in a Direct Injection Diesel Engine: For a Small Scale Non-Grid Electrification. *Energy and Environment Research*, 5(1). doi:10.5539/eer.v5n1p18
14. Lin, H., Huang, M., Luo, J., Lin, L., Lee, C., & Ou, K. (2010). Hydrocarbon fuels produced by catalytic pyrolysis of hospital plastic wastes in a fluidizing cracking process. *Fuel Processing Technology*, 91(11), 1355-1363. doi:10.1016/j.fuproc.2010.03.016
15. Mani, M., Subash, C., & Nagarajan, G. (2009). Performance, emission and combustion characteristics of a DI diesel engine using waste plastic oil. *Applied Thermal Engineering*, 29(13), 2738-2744. doi:10.1016/j.applthermaleng.2009.01.007
16. Marco, I. D., Caballero, B., Torres, A., Laresgoiti, M. F., Chomón, M. J., & Cabrero, M. A. (2002). Recycling polymeric wastes by means of pyrolysis. *Journal of Chemical Technology & Biotechnology*, 77(7), 817-824. doi:10.1002/jctb.636
17. Menges, G., & Berndtsen, N. (1977). Polyvinyl Chloride - Processing And Structure. *Polyvinylchloride-2*, 597-613. doi:10.1016/b978-0-08-021203-6.50007-3
18. Miandad, R., Barakat, M., Aburizaiza, A. S., Rehan, M., Ismail, I., & Nizami, A. (2016). Effect of plastic waste types on pyrolysis liquid oil. *International Biodeterioration & Biodegradation*, 119, 239-252. doi:10.1016/j.ibiod.2016.09.017
19. Muhammad, C., Onwudili, J. A., & Williams, P. T. (2015). Thermal Degradation of Real-World Waste Plastics and Simulated Mixed Plastics in a Two-Stage Pyrolysis-Catalysis Reactor for Fuel Production. *Energy & Fuels*, 29(4), 2601-2609. doi:10.1021/ef502749h
20. "Odluka o regulisanoj ceni električne energije na garantovanom snabdevanju 01.10.2017."* ("Sl. glasnik RS" no. 79/2017) *Decision on regulated price of electricity for guaranteed supply
21. Owusu, P. A., Banadda, N., Zziwa, A., Seay, J., & Kiggundu, N. (2018). Reverse engineering of plastic waste into useful fuel products. *Journal of Analytical and Applied Pyrolysis*, 130, 285-293. doi:10.1016/j.jaap.2017.12.020
22. Papuga, S., Gvero, P., & Vukic, L. (2016). Temperature and time influence on the waste plastics pyrolysis in the fixed bed reactor. *Thermal Science*, 20(2), 731-741. doi:10.2298/tsci141113154p
23. Plastic Europe – Association of plastic manufacturers, (01.04.2018.). *Plastics – The facts*, Publication for 2017, retrieved from https://www.plasticseurope.org/download_file/force/1055/181
24. Prokic, D., & Mihajlov, A. (2012). Contaminated sites. Practice of solid waste management in a developing country (Serbia). *Environment Protection Engineering*, 38(1), 81e90.
25. Scheirs, J. (2006). Overview of Commercial Pyrolysis Processes for Waste Plastics. *Feedstock Recycling and Pyrolysis of Waste Plastics*, 381-433. doi:10.1002/0470021543.ch15
26. Sogancioglu, M., Ahmetli, G., & Yel, E. (2017). A Comparative Study on Waste Plastics Pyrolysis Liquid Products Quantity and Energy Recovery Potential. *Energy Procedia*, 118, 221-226. doi:10.1016/j.egypro.2017.07.020
27. Stauffer, E. (2003). Concept of pyrolysis for fire debris analysts. *Science & Justice*, 43(1), 29-40. doi:10.1016/s1355-0306(03)71738-9
28. "Uredba o obeležavanju (markiranju) derivata nafte"* ("Sl. glasnik RS" no. 51/2015 and 5/2017) *Decree on the marking of oil derivatives
29. "Uredba o planu smanjenja ambalažnog otpada za period od 2015. do 2019. godine"* ("Sl. glasnik RS" no. 144/2014) *Regulation on the establishment of the packaging reduction plan for the period from 2015 to 2019
30. Vorkapic, R., Ocic, O., Kursubic, L., & Jovanovic, B. (2010). Serbia: A new process for waste rubber and plastic recycling. *Perspectives of Innovations, Economics and Business*, 105-108. doi:10.15208/peib.2010.29
31. Vorkapic, R., Ocic, O. and Kurcubic, L., 2006. "Business plan", Competition for the best technology innovation in 2006 in Serbia (in Serbian).
32. Vujic, G., Jovicic, N., Babic, M., Stanisavljevic, N., Batinic, B., & Pavlovic, A. (2010). Assessment of plastic flows and stocks in Serbia using material flow analysis. *Thermal Science*, 14 (Suppl.), 89-95. doi:10.2298/tsci100621031v

33. Williams, E. A., & Williams, P. T. (1997). The pyrolysis of individual plastics and a plastic mixture in a fixed bed reactor. *Journal of Chemical Technology & Biotechnology*, 70(1), 9-20. doi:10.1002/(sici)1097-4660(199709)70:13.3.co;2-5
34. Wu, J., Chen, T., Luo, X., Han, D., Wang, Z., & Wu, J. (2014). TG/FTIR analysis on co-pyrolysis behavior of PE, PVC and PS. *Waste Management*, 34(3), 676-682. doi:10.1016/j.wasman.2013.12.005
35. Xingzhong, Y. (2006). Converting Waste Plastics into Liquid Fuel by Pyrolysis: Developments in China. *Feedstock Recycling and Pyrolysis of Waste Plastics*, 729-755. doi:10.1002/0470021543.ch28
36. "Zakon o akcizama"* ("Sl. glasnik RS" no. 18/2018) *Law on excises