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Feature Articles

Can Non-Recyclable Plastic Waste Be Made Environmentally Sustainable?

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Abstract. After death the fraction of living matter which is not biodegraded (shells, bones, corals, carbonaceous deposits) becomes environmentally sustainable. This is not the case for plastics so that these wastes should be either recycled or made environmentally inert and stored in secure repositories as a resource for future generations. Chemistry has offered different solutions to this problem, and each brings about advantages and disadvantages when compared to other options. One further possible route could consist in the enrichment of the plastics waste in carbon content ("carbonization"), in analogy with the production of charcoal from wood, but we hope to stimulate a debate about all the other possible routes among scientists and engineers in the involved fields.

Keywords: plastics waste accumulation and dispersion, circular economy, carbonization of plastics waste.

1. INTRODUCTION

There is a growing concern about the accumulation and dispersion of plastics waste.[1-4] Plastics have become indispensable for human life and for industry, but their high chemical stability makes most of them not completely degradable when dispersed in soil, fresh and sea water, and in air, unless it was properly designed to be biodegradable. Most plastics are obtained from fossil oil,up to about 10-12 % of the global production, according to an IEA report published in 2018.[3] Even using the best plastic waste management practices,[5-9] models predict that an important fraction of plastics waste (more than 22% in 2050) will accumulate,[10] especially in surface water and oceans, reaching a mass of 500±100 Mt in 2050.[3]

In oceans these wastes are able to create true plastic islands, that reached in 2018 an overall surface of $1.6{\cdot}10^6$ km^2, corresponding to about 6 times the surface of France, in the Pacific Ocean only.[3] Plastics waste degradation is accelerated by irradiation from the UV component of sunlight and by some mechanical wearing, with the continuous production of smaller and smaller debris, maintaining a substantial chemical integrity.[11-17] Energy recovery as heat, steam, or electricity by burning plastics wastes, that in 2016 represented the fate of as much as 40% of plastics waste,[3] is strongly discouraged because of the production of greenhouse gases and pollutants.[1-3,13] As it will be better detailed below, different strategies have been proposed for reusing and recycling plastics waste,[18] but its large fraction that accumulates in landfills and, what is much more dismaying, in surface waters and oceans, is generally not adequately considered. Although we are not pure specialists in the field, general common sense considerations led us to give our little contribution to drive the attention of the scientific community of chemists to this important problem in order to be allowed to say "I do my part of the job"

2. CIRCULAR ECONOMY AND PLASTICS WASTE

There are several different ways to define circular economy. According to the European Commission's Implementation of the Circular Economy Action Plan, approved in 2019, Circular Economy is:

> A system aimed at eliminating waste, circulating and recycling products, and saving resources and the environment.[19]

In a recent review focused on the plastics waste, it is stated that:[9]

> [the] concept of "circular economy" (CE) commonly refers to the "take-make-use-break-make" concept, where the main goal is to create economic impetus from the waste. It also enables the close-looping of product – waste – building block cycle.

However, as remarked for instance by Kümmerer *et al.*,[5] a complete recycling of plastics waste is practically impossible, unless plastics materials are purposely designed, and in fact a huge amount of wasted plastic residues is actually dispersed in the environment.

A closer look at natural living systems action to maintain environmental sustainable cycles can give some further insight in extending the concept of circular economy. Indeed, after completing their vital cycle, the fate of living matter "waste", besides a small quantity of volatile compounds, which are dispersed in the atmosphere, water or in soil, is mostly bio-recycled. Only a negligible fraction of it is burned as a consequence of natural events, such as fires caused by lightning, or by volcanic eruptions. However, a more or less important fraction of living matter waste is made of mineralized remnants. For instance, bones buried in soil last nearly unchanged for centuries, shells of aquatic animals are accumulated in lakes, seas, oceans floors and eventually become rocks, and coral colonies are able to build up entire islands. Finally, fossil carbonaceous deposits (coal, oil and natural gas) were originated by large amounts of living matter deeply sunk in soil. All these long-lasting living matter wastes share the important property to be environmentally sustainable, or inert. In conclusion, the natural ecology *is not strictly circular*, but the produced "waste", which is not recyclable is *environmentally sustainable*. Therefore, it is reasonable to ask ourselves why we cannot follow a similar route for the management of plastics waste, by proposing that all what cannot be biodegraded or used as feedstock for recycling[18] shall be treated to become environmentally inert and stocked in secure repositories, for future use as matter and energy resource.

3. OVERALL MANAGEMENT OF THE PLASTICS WASTE

Plastics often consist in one or more co-polymers along with several additives such as plasticizers, flame retardants, coloured agents, ultraviolet-light stabilizers, antioxidants that are difficult to separate during the recycle process leading to waste of time, money and material. The bottleneck of recycling is the preliminary separation and fractionation of the present compounds. Therefore recycling is often considered only at the atomic or molecular level with possible loss of the intrinsic properties of the products compared to those of the same products in the original waste. In January 2018 the European Commission announced a vision for Europe's new plastics economy substantially based on a new model of economy: from linear to circular economy. So the following commitments are considered to be implemented:

- all plastic packaging used in Europe must be reused or recycled by 2030;
- more than half of the plastic wastes must be recycled;
- plastic sorting and recycling capacity must be extended fourfold by 2030:
- some 10 million tons of recycled plastics are to be used for new products by 2025.

Mechanical recycling consists in transforming the plastic waste in raw material without any substantially modification of its chemical structure. It is the largely most adopted method in Europe but due to the presence of additives the process cannot recover more than 60-70% of the original wastes. The recycled materials find the same application as the original plastic wastes, in any sector of our today common life.

If separation and filtration of additives is omitted to save time and money, the obtained products are mainly used in mixed formulations applied to building works such as streets, bridges and other infrastructures. An alternative way is based on a selective dissolution of the plastic waste followed by filtration and evaporation of the solvent, but the real innovative process of recycle is based on chemical and biotechnological processes especially applied in the case of wastes of polyethylene terephthalate (PET), nylon and polyurethane. Among the chemical processes, pyrolysis consists in heating under vacuum which will result in a final product that contains a mixture of liquid and gaseous hydrocarbons.[4,20-23] De-polymerization can be obtained, at least for PET by means of microwave radiation.[24] Hydrogenation is a degradation that involves a treatment with hydrogen followed by heating, and in this case the products are olefinic hydrocarbons (ethylene, propylene, butadiene). Gasification is obtained by heating at high temperature (800-1600 °C) in the absence of air that results in a mixture of hydrogen and carbon monoxide. Chemolysis, glycolysis, methanolysis, amminolysis are all de-polymerisation processes that produce low molecular weight products, which can be used as reagents of multiple synthetic reactions and represent *an alternative route*, that results in the formation of chars (solid carbonaceous materials) and gaseous hydrocarbons. However, these solutions do not contribute to the "decarbonisation" of our society: the products are intended to be used as fossil fuels so contributing to further increase the anthropogenic greenhouse effect.

An innovative way of recycling is the enrichment of plastics wastes in C content. This process leads also to the recover of hydrogen and other heteroelements. The final products can be stored in the same sites where the raw material was extracted, such as exhausted carbon mines and fuel deposits, reproducing a stock of inert raw material to be used in the future.[25]

The main problem of this option is to have the proper catalyst able for the extraction of hydrogen and other elements similarly to what was obtained with the charcoal from the thermal treatment of wood. As recently reported, a catalyst based on mixed iron and aluminum oxides acting under a microwave field of 1000 W seems to be able to extract hydrogen from plastics.

Also biotechnological methods were successfully applied to the recycling of plastics.[6] The discovery made by a group of researchers of Carbios and of the Toulouse Institute of Biotechnology[26] of an enzyme present in the leaves' compost has opened a new way to recycle PET with very promising results as the recycled material has the quite same properties of the original waste.

In the 25th August 2020 issue of the *Chemistry World* weekly Kyra Welter reports that an International Group of research was successful in obtaining a polymer able to be recycled in principle for an infinite number of times, during which it was depolymerized and the obtained monomer was re-polymerized and so on.[27,28] Contrary to mechanical recycling that changes the properties of the material after few cycles, monomerization can potentially bring to materials that can be recycled whenever needed without any limit and keeping the same properties of the raw starting material. The problem in this case is that monomerization, if not purposely designed for plastic materials is not an available chemical process.

The chemical modification of the existing hardly recyclable plastics can increase their lifetime and face three different problems: first, in general polymers easily decomposed do not present good properties; second, the obtained products behave better in many common applications; and, third, if one wants to have good mechanical properties for the new product it is necessary to control the stereochemistry of the polymerization. The integration of this option in the actual recycling systems could be difficult because of the multifarious variety of the plastic waste, increasing the number of the possible components. This point can only be solved by a very responsible behavior of citizens and of local Institutions.

In general, plastics waste treatment can entail a net cost, which is to be supported in view of the unbearable environmental damage of accumulation and dispersion of plastics waste.[4] In line with a recent proposal about carbon taxes, this cost should be recovered from special *ad hoc* taxes "*similar to a value added tax (VAT) [...] such that end users pay the full costs*.".[29] Indeed general taxation usually is not equally charged and distributed among taxpayers.[30] Note that actually many megatons per year of plastics waste are exported from Europe, Australia and North America to China and other countries,[3,4] entailing transport costs that could be avoided if sustainable domestic treatments are properly implemented.

4. DISCUSSION AND CONCLUSIONS

In this paper we shortly outlined some dismaying problems connected with the management of plastics wastes, and particularly, of the large fraction of this waste which is accumulated untreated in landfills as well as in surface and sea waters, even if an increasing commitment is advanced to reuse and recycle plastics waste by the various available procedures.[1] Any effort and strategy should be performed to avoid the dispersion of plastics waste in air, waters and soil, by securing and controlling any phase of deposit, and especially in the long-lasting landfills.

As remarked, in view of the global warming problems, it should also avoided and restricted any treatment of plastics waste releasing CO_2 and other greenhouse gases into the atmosphere. In addition, the products of plastics waste recycling suitable as fuels should be preferably if not mandatorily used as feedstock for the chemical industry, so sparing mineral oil resources, or stored in secure repository.

A general strategy for the plastics waste management was proposed in the conclusions of a recent review about microplastics (tiny specks of plastics of micrometer size) by Hale *et al.*:[13]

> Most plastics are inexpensive to manufacture. Hence, there is little financial incentive to reuse them. To support a circular lifecycle, the upfront price of plastics must incorporate end of life costs. Currently, low volume plastic users and associated ecosystems bear a disproportionate burden (e.g., remote islands are now being littered with plastic debris). This environmental injustice echoes that of climate change and sea level rise. Landfills may be mined by future generations as resources become scarce and technologies improve. Optimization of such "dumps" into "repositories" is worthy of consideration. Political initiatives across borders should seek to accomplish these goals.

However, by considering the amounts and the rate of accumulation in landfills, in our opinion it is urgent to find also sustainable technical routes to transform the untreated or not recyclable plastics waste into "inert" matter which should be stored in secure repositories, such as exhausted mines of coal and other minerals, or impermeable quarries, as a resource for future generations. It could be objected that a large fraction of plastic waste is already environmentally "inert", as it lasts almost unchanged for hundreds or even thousands of years,[14] if properly saved. There are at least two reasons to propose a further treatment of plastic waste. First, the chemical nature of plastic materials makes their use as a feedstock in the future rather difficult and expensive, so that saving more homogenous materials would be preferable. The second reason is that the recovery of hydrogen, fluorine and other elements could help in reducing or even offset the cost of the treatment. In addition, the danger of a dispersion of degraded plastics in air and waters (especially as microplastics) would be contrasted, and the amount of the final waste could be reduced. All this can be obtained by the enrichment of the plastics waste in C content ("carbonization"). Examples of chemical processes that can achieve this result are discussed by Chen *et al.*[25]

If this proposal is considered unpractical or too expensive, we wonder whether there are there other ways to obtain environmentally sustainable materials from plastics waste.

In conclusion, on one hand, we urge scientists and engineers working in the field of plastics materials to think and propose practical solutions to this problem, and on the other hand we hope that a fruitful discussion about the ways to avoid accumulation and dispersion of plastics wastes will involve a larger scientific, technological, political and especially social public.

REFERENCES

1. United Nations Environment Programme, *Converting Waste Plastics into a Resource. Compendium of Technologies. Assessment Guidelines*, Division of Technology, Industry and Economic International Environmental, Technology Centre Osaka/Shiga, United Nations Environment Programme (UNEP), **2009**. https://wedocs.unep.org/bitstream/handle/20.500.11822/8638/WastePlasticsEST_Compendium_full.pdf?sequence=3&isAllowed=y.
2. OECD *Background Report: Improving Plastics Management: Trends, Policy Responses, and the Role of International Co-operation and Trade, Environment Policy Paper No. 12*, OECD, **2018**, https://www.oecd.org/environment/waste/policy-highlights-improving-plastics-management.pdf.
3. IEA, *The Future of Petrochemicals. Towards more sustainable plastics and fertilizers*, IEA, **2018**, https://www.iea.org/reports/the-future-of-petrochemicals.
4. EASAC, *Packaging Plastics in the Circular Economy. EASAC policy report 39*, **2020**. https://easac.eu/publications/details/packaging-plastics-in-the-circular-economy/
5. K. Kümmerer, J. H. Clark, V. G. Zuin, *Science* **2020**, *367*, 369-370. DOI: 10.1126/science.aba4979.
6. F. Zhang, Y. Zhao, D. Wang, M. Yan, J. Zhang, P. Zhang, T. Ding, L. Chen, C. Chen, *J. Cleaner Production* **2021**, *282*, 124523. DOI: 10.1016/j.jclepro.2020.124523.
7. Y. A. Hidayat, S. Kiranamahsa, M. A. Zamal, *AIMS Energy* **2019**, *7*, 350–370. DOI: 10.3934/energy.2019.3.350
8. A. K. Awasthi, M. Shivashankar, S. Majumder, *IOP Conf. Series: Materials Science and Engineering* **2017**, *263*, 022024. DOI: 10.1088/1757-899X/263/2/022024.
9. D. K. Bora, *MRS Energy & Sustainability* **2020**, *7*, 28. DOI: 10.1557/mre.2020.28.
10. W. W. Y. Lau, Y. Shiran, R. M. Bailey, E. Cook, M. R. Stuchtey, J. Koskella, C. A. Velis, L. God-

frey, J. Boucher, M. B. Murphy, R. C. Thompson, E. Jankowska, A. Castillo Castillo, T. D. Pilditch, B. Dixon, L. Koerselman, E. Kosior, E. Favoino, J. Gutberlet, S. Baulch, Me. E. Atreya, D. Fischer, K. K. He, M. M. Petit, U. Rashid Sumaila, E. Neil, M. V. Bernhofen, K. Lawrence, J.E. Palardy, *Science* **2020**, *369*, 1455-1461. DOI: 10.1126/science.aba9475.

11. K. Min, J. D. Cuiffi, R. T. Mathers. *Nature Commun.* **2020**, *11*, 727. DOI: 10.1038/s41467-020-14538-z.
12. G. Birarda, C. Buosi, F. Caridi, M. A. Casu, G. De Giudici, L. Di Bella, D. Medas, C. Meneghini, M. Pierdomenico, A. Sabbatini, A. Surowka, L. Vaccari, *Environ. Pollut*. **2021** in Press. DOI: 10.1016/j.envpol.2021.116912.
13. R. C. Hale, M. E. Seeley, M. J. La Guardia, L. Mai, E. Y. Zeng, *J. Geophys. Res.: Oceans* **2020**, *125*, e2018JC014719. DOI: 10.1029/2018JC014719.
14. A. Chamas, H. Moon, J. Zheng, Y. Qiu, T. Tabassum, J. H. Jang, M. Abu-Omar, S. L. Scott, S. Suh, *ACS Sustainable Chem. Eng.* **2020**, *8*, 3494-3511. DOI: 10.1021/acssuschemeng.9b06635.
15. X. Zh. Lim, *Nature* **2021**, *593*, 22-26. DOI: 10.1038/d41586-021-01143-3.
16. N. H. M. Nor, M. Kooi, N. J. Diepens, A. A. Koelmans, *Environ. Sci. Technol.* **2021**, *55*, 5084. DOI: 10.1021/acs.est.0c07384.
17. Y. Picó, D. Barceló, *ACS Omega* **2019**, *4*, 6709–6719. DOI: 10.1021/acsomega.9b00222.
18. ISO 15270:2008(en) *Plastics - Guidelines for the recovery and recycling of plastics waste*, **2008**. https://www.iso.org/obp/ui/#iso:std:iso:15270:ed-2:v1:en
19. European Commission, *Implementation of the Circular Economy Action Plan*, Brussels, **2019**. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0098&from=EN.
20. G. Lopez, M. Artetxe, M. Amutio, J. Bilbao, M. Olazar, *Renew. Sustain. Energy Rev*. **2017**, *73*, 346 –368. DOI: 10.1016/j.rser.2017.01.142.
21. H. Rubel, U. Jung, C. Follette, A. Meyer zum Felde,. S. Appathurai, M. B. Díaz, A Circular Solution to Plastic Waste, Boston Consulting Group, Boston, **2019**. https://image-src.bcg.com/Images/BCG-A-Circular-Solution-to-Plastic-Waste-July-2019_tcm9-223960.pdf.
22. A. Rahimi, J. M. García, *Nature Rev. Chem.* **2017**, *1*, 0046. DOI: 10.1038/s41570-017-0046
23. I. Vollmer, M. J. F. Jenks, M. C. P. Roelands, R. J. White, T. van Harmelen, P. de Wild, G. P. van der Laan, F. Meirer, J. T. F. Keurentjes, B. M. Weckhuysen, *Angew. Chem. Int. Ed.* **2020**, *59*, 15402–15423. DOI: 10.1002/anie.201915651.
24. DEMETO Project. https://www.demeto.eu/project
25. S. Chen, Z. Liu, Sh. Jiang, H. Hou *Sci. Total Env* **2020**, *710*, 136250. DOI: 10.1016/j.scitotenv.2019.136250.
26. Tournier, V., Topham, C.M., Gilles, A, B. David, C. Folgoas, E. Moya-Leclair, E. Kamionka, M.-L. Desrousseaux, H. Texier, S. Gavalda, M. Cot, E. Guémard, M. Dalibey, J. Nomme, G. Cioci, S. Barbe, M. Chateau, I. André, S. Duquesne, A. Marty, *Nature* **2020**, *580*, 216–219. DOI: 10.1038/s41586-020-2149-4.
27. C. Shi, M. L. McGraw , Z.-C. Li, L. Cavallo, L. Falivene, E. Y.-X. Chen, *Sci. Adv*. **2020**, *6*, eabc0495. DOI: 10.1126/sciadv.abc0495
28. K. Welter**,** *Chem. World* **2020**, 25 August. https://www.chemistryworld.com/news/designer-plastic-can-be-recycled-over-and-over-again/4012317.article.
29. S. Tagliapietra, G. B. Wolff, *Nature* **2021**, *591*, 526-528. DOI: 10.1038/d41586-021-00736-2.
30. T. Piketty, *Capital et idéologie*, Éditions du Seuil, Paris, **2019** [Engl. Ed.: T. Piketty, *Capital and ideology*, Harvard University Press, Cambridge, USA, **2020**]