23 January 2024

Rebuttal to Chemical Recycling Europe's position paper on Zero Waste Europe's pyrolysis report: '*Beyond the headline criticism, elaboration is lacking in their Position Paper*'

As a scientific report, 'Leaky loop "recycling" – A technical correction on the quality of pyrolysis oil made from plastic waste', published by Zero Waste Europe on 26th October 2023 (hereafter called *Leaky Loop "Recycling"*), was written in a way that permits it to be tested for robustness. This enables science to stand under scrutiny and rebut baseless criticisms, such as those recently made by Chemical Recycling Europe in their Position Paper made public on 11th December 2023 (hereafter called CRE Position Paper).

Leaky Loop "Recycling" was a meta-research report. Its methodology, commonly called 'literature review', collated previous experimental research to derive new conclusions. Specifically, it analysed *twenty-two* independent peer-reviewed empirical research papers that had assessed the quality of pyrolysis oil made from predominantly polyolefin plastic waste, along with a further *six* independent peer-reviewed empirical research papers that had assessed more difficult plastic waste streams. ZWE report also drew from independent meta-research on the same topic involving more than *forty* independent empirical research studies (meta- meta-research). All are listed in its Appendices. Calling them "a narrow set of inconclusive evidence" is incomprehensible.

Since the findings of *Leaky Loop "Recycling"* derive from other independent researchers and authors, it is unclear where the charge of "*grave misinterpretation of facts and scientific evidence*" comes from. Indeed, other authors suggest the need to blend pyrolysis oil with 80 to 95% petroleum naphtha, while some identify that the oil is over a thousand times off specification. For example:

"[...] pyrolysis oil can neither replace nor be blended with naphtha and is not a viable option for closing the circularity of waste plastics [...]. The results demonstrate that although there is a very small fraction of pyrolysis oil consisting of saturated alkanes and cycloalkanes, pyrolysis oil obtained from PP [polypropylene] exhibits distinct compositional differences than naphtha and cannot be used as a substitute for it."[1]

"Contaminant levels exceed established feedstock quality specifications by one or more orders of magnitude such as for nitrogen, chlorine and iron. All these contaminants are known to cause corrosion issues, increase coke formation, destroy expensive reactor tubes or deactivate catalysts in the separation sections of a steam cracker. Even the typical amounts of olefins, oxygenates and aromatics found in plastic waste pyrolysis oils are substantially off-spec. ***In a nutshell, today the***

[1] Erkmen, B., Ozdogan, A., Ezdesir, A., Celik, G. 2023. Can pyrolysis oil be used as a feedstock to close the gap in the circular economy of polyolefins? *Polymers*, **15**, 859.

quality of crude plastic waste pyrolysis oils is unacceptable as feedstocks for industrial steam crackers."[2]

Are CRE saying that these independent authors are also misrepresenting facts?

No robust evidence is provided by CRE to support their charges. Beyond the headline criticism, elaboration is lacking in their Position Paper. Its content is largely rhetorical, lacking substance to prove the claims.

All CRE provides as support for their accusations are two website pages and two literature life cycle assessments (LCA). In addition, there is a link to the EU Waste Framework Directive.

CRE claims that "*There is a wealth of research and data that could have been used to draw conclusions on the status quo of pyrolysis*". Still, they do not provide any. While the ZWE report cites dozens of peer-reviewed research papers to conclude such status.

Ironically, the CRE Position Paper cites an LCA report that refutes CRE's own claims, i.e. that "*[life cycle] assessments are rooted in empirical data obtained from technology providers*". On the contrary, here is what their reference says[3]:

"***Despite repeated attempts at obtaining survey-based information from operators**, which could help identify the key conditions under which chemical recycling can function optimally from a technical point of view (e.g. safety, yield, predictable quality of output), **no such input was received**.*"

There are other problems with this reference. It compares the results with incineration as end-of-life treatment rather than with virgin plastic production, findings only show positive GHG benefits for chemical recycling of PS and PET when PET is not a feedstock for pyrolysis, vagueness about whether dilution/upgrading has been incorporated into the model, nor the full extent of dilution required.

For these reasons, LCAs of plastic waste pyrolysis were specifically and unreservedly excluded from the scope of *Leaky Loop "Recycling"*. LCAs are accepted by many authors to be wildly untrustworthy[4] [5]. Yet, examples of flawed industry-funded LCA models still continue, such as one recently that assumes the impossible scenario of pyrolysis operating as a perpetual motion machine driven only by its own product gas (SI, Table S6), and appears to assume no yield losses, meaning

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[2] Kusenberg, M., Eschenbacher, A., Djokic, M.R., Zayoud, A., Rageart, K., De Meester, S., Van Geem, K.M. 2022. Opportunities and challenges for the application of post-consumer plastic waste pyrolysis oils as steam cracker feedstocks: To decontaminate or not to decontaminate? *Waste Management*, **138**, pp. 83-115.

[3] Garcia-Gutierrez, P., Amadei, A.M., Klenert, D., Nessi, S., Tonini, D., Tosches, D., Ardente, F., Saveyn, H. 2023. Environmental and economic assessment of plastic waste recycling. A comparison of mechanical, physical, chemical recycling and energy recovery of plastic waste. Joint Research Centre. Publications Office of the European Union: Luxemburg.

[4] Pires Costa, L., Micheline, D., de Miranda, V., Pinto, J.C. 2022. Critical evaluation of life cycle assessment analyses of plastic waste pyrolysis, *Sustainable Chemistry and Engineering*, **10**, pp. 3799-3807.

[5] Tabrizi, S., Rollinson, A.N., Hoffmann, M., Favoino, E. 2020. Understanding the environmental impacts of chemical recycling. Ten concerns with existing life cycle assessments. Zero Waste Europe: Brussels.

that 100% plastic produces 100% pyrolysis oil[6]. While a model produced by independent researchers the same year found that pyrolysis was 10 to 100 times *worse* environmentally than virgin plastic production[7].

Despite fifty years of endeavour, heavy investment by large multinational corporations which failed, and all the plants' industry would have us believe is 'soon to be', **where is all the evidential data of effective operation**? It does not exist, or the actual results are so poor that they are not disclosed. The reason is the intrinsic obstructing nature of pyrolysis, as described in *Leaky Loop "Recycling"*, written by a pyrolysis engineer, and quoting other pyrolysis engineers who admit that the problems are unsolved[8].

Another empty accusation made by CRE is that *Leaky Loop "Recycling"* did not "*contextualize that there are a wide range of pyrolysis process configurations and different arrangements with each of these producing different oil grades…"* This statement is verifiably false, you can refer to the Appendices of *Leaky Loop "Recycling*" for a comprehensive dataset covering a full range of pyrolysis parameters, including catalytic, fast, slow, highest treatment temperatures, multiple ramp rates, yielding oil quantity from 5% to 89%.

This also rebuts the CRE criticism that *Leaky Loop "Recycling" "[drew] conclusions based on a narrow set of inconclusive evidence to obscure facts"*. Again, there is no substance to this charge from CRE and no comparable evidence is offered in return.

These, like many quotes made by CRE, are common industry stock phrases and it is no surprise to hear other clichés, such as "*pyrolysis is currently undergoing rapid technological advances*". Granted, more talk is made about the process and more efforts are being made to implement it, but technically pyrolysis of plastic waste is stagnant and beset by the same obstacles that have blighted it in the past. The reasons for this were outlined in *Leaky Loop "Recycling"*, technical aspects which, by the way, CRE did not comment on.

Overused phrases supplement an industry PR narrative that relies on flawed LCAs and the premise of chemical recycling being always on the brink of success, or perpetually on the horizon. Since even the industry admits it is struggling with pyrolysis and its major challenges it would be better if CRE explained just what advances have been made in the last five, ten, fifteen years, and provided independent data of operational performance on parameters such as energy balance, yield, oil and waste by-product toxicity.

Still, it is however surprising to read in the CRE Position Paper the claim that pyrolysis can accept mixed plastic waste streams. This tired statement is refuted by independent authors, conflicts with

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[6] Gracida-Alvarez, U.R., Benavides, P.T., Lee, U., Wang, M. 2023. Lifecycle analysis of recycling of post-use plastic to plastic via pyrolysis. Journal of Cleaner Production, 425, 138867.

[7] Uekert, T., Singh, A., DesVeaux, J.S., Ghosh, T., Bhatt, A., Yadav, G., Afzal, S., Walzberg, J., Knauer, K.M., Nicholson, S.R., Beckham, G.T., Carpenter, A.C. 2023. Technical, economic, and environmental comparison of closed-loop recycling technologies for common plastics. ACS Sustainable Chemistry and Engineering, 11, pp. 965-978.

[8] Tulla, A.H. 2022. Amid controversy, industry goes all in on plastic pyrolysis (online). Accessed 30th December 2023. Available from: https://cen.acs.org/environment/recycling/Amid-controversy-industry-goes-plastics-pyrolysis/100/i36

established science, and perhaps most tellingly is refuted by pyrolysis operators themselves (Section 7.2 of Leaky Loop "Recycling").

The CRE Position Paper states that "*It is critical to recognize that the majority of pyrolysis capacity, whether currently operational or planned, primarily targets mixed post-consumer or post-industrial plastic waste*". Indeed, this is exactly why *Leaky Loop "Recycling*" focussed on polyolefins (PE and PP) most of which had been thoroughly pre-treated by sorting and washing (see Appendix dataset).

Separately, *Leaky Loop "Recycling"* did explore the additional problems of waste streams such as ASR and computer casings. These, as expected, yield an oil of far worse quality, but it is not therefore that only these 'difficult' streams cause problems that need upgrading, as CRE implies.

Elsewhere CRE are confused with regards to wood and cellulose. *Leaky loop "Recycling"* does not refer to these as contaminants, merely mentions how plastic feedstock produces more PAHs than cellulosic material when subjected to pyrolysis.

With regard to the steam cracker limit values, or "*contaminant limits*", these were taken from independent peer-reviewed journal papers[9] [10]. Though specificity *was* discussed in *Leaky Loop "Recycling"*, it was beyond the scope to go in-depth into each contaminant, rather the references were cited, as is conventional.

Dioxins *do* form during pyrolysis, in greater quantities than incineration, and they carry over in high concentrations into pyrolysis oil. This has been reported by many independent studies (§6.2.2 of *Leaky Loop "Recycling"*). While CRE says that the matter is "*controversial*", this is untrue, rather it is under-reported. The following are scientific facts:

1. Pyrolysis creates PAHs that are precursors to dioxins.
2. These, and the dioxins that form, are not destroyed by pyrolysis (as they can be in incineration) but are preserved in the oil and char products.
3. Oxygen *is* present in pyrolysis (pyrolysis is a low-, rather than a no-, oxygen process).
4. Chlorine is ubiquitous in plastic waste (not merely PVC) through its wide use as an additive and as a non-intentionally added substance, and only small amounts are needed during the pyrolysis route to dioxin formation. Obviously CRE, by their assertions, is muddled with the 'de-novo' synthesis formation route. The topic is a great cause for public concern and needs more research focus.

Ultimately, the CRE Position Paper actually agrees with the findings of *Leaky Loop "Recycling"* that "*dilution is the only feasible option to off-take pyrolysis oil for polymer production*". What *Leaky Loop "Recycling"* did show, based on empirical data, was that at best the process will use only 2% recycled plastic needing dilution with 98% petroleum naphtha. It then went on to highlight **this is**

[9] Kusenberg, M., Eschenbacher, A., Djokic, M.R., Zayoud, A., Rageart, K., De Meester, S., Van Geem, K.M. 2022. Opportunities and challenges for the application of post-consumer plastic waste pyrolysis oils as steam cracker feedstocks: To decontaminate or not to decontaminate? Waste Management, 138, pp. 83-115.

[10] Kusenberg, M., Faussone, G.C., Dao Thi, H., Roosen, M., Grilc, M., Eschenbacher, A., De Meester, S., Van Geem, K.M. 2022. Maximising olefin production via steam cracking of distilled pyrolysis oils from difficult-to-recycle municipal plastic waste and marine litter, Science of the Total Environment, 838, 156092.

exactly why the industry is pushing for manipulative and flexible mass balance accounting, which in one swipe allows them to surreptitiously claim that their product is 100% recyclable. The public has a right to know this for purposes of transparency.

Consequently, pyrolysis of plastic waste further strengthens petrochemical production linearity. It can never be a circular economy option for plastics. The matter is exacerbated by the fact that large quantities of fossil fuels must be burned to provide energy for the pyrolysis process[11].

Since CRE admits that "*dilution is the only feasible option*", and the actual quantification is now known, it is hard to see how this can be reconciled with vague statements made by CRE such as "*the challenge of achieving plastic circularity requires multiple sustainable solutions working together*".

Though the CRE Position Paper says that the goal of the industry is to "*scale these quantities to replace naphtha*", it does not explain how it is ever going to be achieved, and how this will impact the environmental performance (e.g. in terms of used energy and resulting waste from purification). Regulating plastic manufacturers to make products with fewer contaminants would be a start, but this is not in the current EU legislative agenda. Still, this does not address the synthesis of heavy hydrocarbons – toxic, recalcitrant and unwanted in the steam cracker process - that pyrolysis, by its nature, creates.

In conclusion, when making allegations, such as those levelled by CRE, it is essential that they are backed up by robust and independent evidence, otherwise, they are baseless.

The author of *Leaky loop "Recycling"* is willing to engage further with CRE if they would please provide the following: **1.** evidence of proven sustainable operation, at scale, and at steady state; **2.** the quantity and toxicity of both product oil and waste residues from the same; **3.** oil yields; **4.** mass balances that show where all the plastic additives go (many of which are highly hazardous); and **5.** energy balances that show the amount of diesel or natural gas used to operate the pyrolysis process, including energy (and other resources) required to increase the volume of pyrolysis oil (like purification and upgrading).

Science develops by facts based on empirical evidence, not by empty conjecture and wishful thinking.

[11] Rollinson, A.N., Oladejo, J.M. 2019. 'Patented blunderings', efficiency awareness, and self-sustainability claims in the pyrolysis energy from waste sector, Resources, Conservation and Recycling, 141, pp. 233-242.