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The Different Plastics Used in the Laboratory

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Plastic products are ubiquitous in the laboratory and used for various applications. They are made of different plastics such as polypropene (PP), polyethene terephthalate (PET), or polycarbonate (PC). But what are the differences, and why should you pay attention to which plastic the product you use is made of? This White Paper takes a closer look at the plastic variants employed most frequently in the lab, their properties, and their environmental impact.

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Introduction

You use single-use plastic for many types of experiments in the lab: You pipette your cell culture media from a bottle made of PET using pipette tips made of polypropene (PP) to grow your cell culture on plates made of polycarbonate (PC) or polystyrene (PS). Plastic entered the lab many years ago and remained in place for good reasons. Plastic items are versatile and can be produced in various forms and shapes. They are durable, stable, and, in most cases, non-breakable. Sterile single-use plastic items, in particular, are safe - you don't have to worry about contaminants interfering with your experiments. Items made of glass can be an alternative to certain plastic consumables; however, they are not suitable for all applications, and, importantly, glass breakage can be a safety concern in the lab.

But not all plastics are the same, and not every type of plastic is suitable for all applications. This White Paper covers the most common materials used in the lab, their shared features and differences, and the applications for which each type of plastic can be used.

The most common plastic types used in the lab

In the lab, most items and consumables are made of one of the following polymers: polypropene (PP), polyethene (PE), polyethene terephthalate (PET), polycarbonate (PC) or polystyrene (PS). These plastics have different properties, which make them suitable for specific applications. Keep in mind that even the same type of plastic can be more or less resistant to heat, UV-light, stress or certain chemicals. Some items are autoclavable whereas others are not, and some polymers such as PP are suitable for molecular biology applications, whereas PET is not.
In general, the plastics used for the manufacture of laboratory consumables are very pure and should not contain critical leachable substances. These consumables are used for sensitive applications where no interference from external contaminations is tolerable [1, 2]. As they are single-grade plastics, these plastic items are considered to be recyclable by material. Due to the contamination of laboratory plastic waste with chemicals and solutions, these plastic items require decontamination which is mainly achieved through incineration.
In addition to decontamination, recycling also depends on further treatment and recycling capacities, whether one can leverage the recycling potential, or whether these items will be downcycled or burned.
Let's look closely at the different types of plastics used in the lab to understand their properties, the consequences for your specific application, and their environmental impact.

Polyethene – the most frequently used polymer worldwide

Polyethene (PE), also known as polyethylene, is by structure the simplest polymer among the olefins and, at the same time, the most widely used plastic in the world. In the lab, lids, beakers, bottles, cylinders, and many more items are made of PE [3-9]. This material is synthesized by polymerizing ethene, resulting in a linear polymer structure of repeating ethene units with a carbon backbone and hydrogen atoms as side groups. As simple as this structure seems, polyethene is offered in very different variants. The most well-known are HDPE (high-density PE), LDPE (low-density PE), and LLDPE (linear low-density PE) [Fig 2]. By changing the manufacturing process, other variants of PE can be synthesized with very different structures.

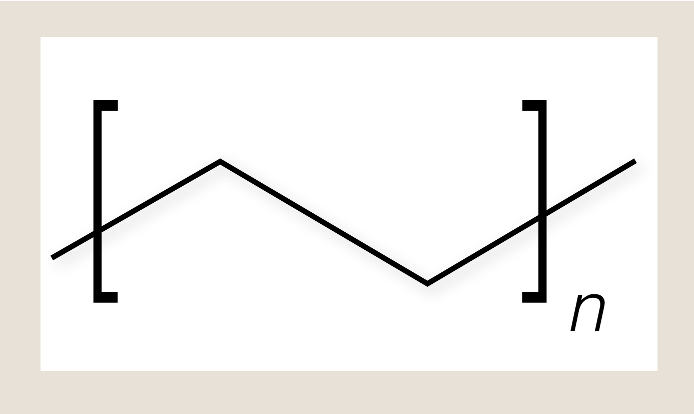

Fig. 1: The chemical structure of polyethene (PE)

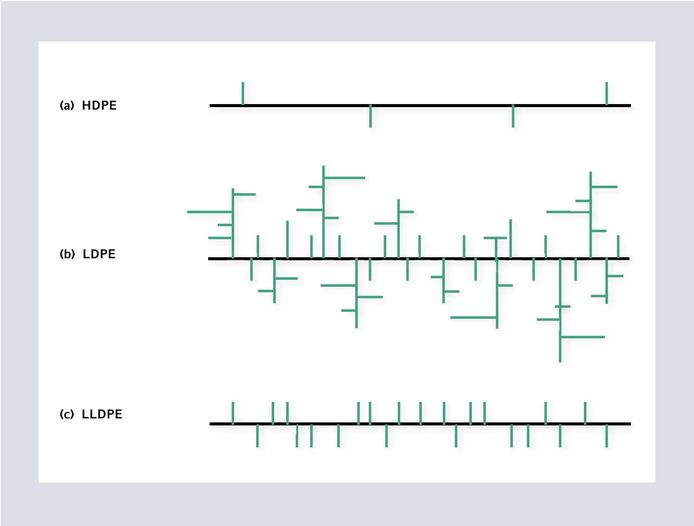

Fig. 2: The three most common variants of polyethene (PE)

Let's look at the different PE variants in more detail:

The first is **High-Density Polyethene** (HDPE) which consists of linear, weakly branched polymer chains which can be closely packed together [Fig. 2a]. As a result, HDPE is a highly crystalline material with a high density (0.941 g/ cm^3 or greater). It is more rigid and stronger compared to other PE variants.

The second variant of PE is **Low-Density Polyethene** (LDPE). LDPE consists of highly branched polymer chains [Fig.2b]. It has a slightly lower density (between 0.91 g/ cm^3 and 0.94 g/ cm^3) than HDPE as the crystallinity is much lower, resulting in increased flexibility.

The last variant is **Linear Low-Density Polyethene** (LLDPE). LLDPE has a lower branching rate than LDPE, and the side chains are shorter. It is synthesized by copolymerization with short-chain olefins such as butene, hexene, or octene [Fig. 2c], which results in a similar density to LDPE, but with lower crystallinity. The properties are very similar to those of LDPE, but LLDPE is stronger, e.g., films made of LLDPE are tear-resistant and flexible. Finally, there are some indications that the production process of LLDPE is less energy-intensive than that of LDPE or HDPE.

Polyethene, in general, displays excellent chemical resistance, for example, to diluted acids and bases, solvents, alcohols, and aliphatic hydrocarbons. PE is not resistant against aromatic or chlorinated hydrocarbons, or to strong acids and bases. It is important to note that chemical resistance varies between different types of PE. In general, the higher the density, the higher the chemical resistance. As mentioned above, HDPE, LDPE, and LLDPE exhibit different crystallinity degrees, affecting their respective melting temperatures, which range between 105-115°C for LDPE and 120-130°C for HDPE. Therefore, items made of PE are non-autoclavable.

What about the environmental impact of PE production as well as the end of its life? Production of 1 kg of HDPE polymer resin requires 80.2 MJ of primary energy, and it takes 82.9 MJ to produce 1 kg of LDPE polymer resin. The manufacturing process also releases 1.8 and 1.87 kilograms of CO_2e, (CO_2 equivalents) respectively [8]. Looking at the end of life, it is worth mentioning that PE is highly recyclable if collected separately. Each type of plastic has a specific recycling code. There are two recycling codes for PE: #2 for HDPE and #4 for both LDPE and LLDPE. However, even if recycling is possible, many PE plastic items are incinerated, independent of whether they originate from the laboratory or in the consumer area. Incineration is not the best solution, but this process is capable of recovering a certain amount of energy. In the case of HDPE, the energy content of 1 kg of polymer resin is equivalent to 34 MJ, and in the case of LDPE, the energy content is slightly higher at 36.7 MJ per kg of polymer resin.

Polypropene – the polymer pipette tips are made of

Let's check the next important type of polymer: Polypropene (PP), well-known as polypropylene, which is globally the second most important plastic. PP is used in the lab, for example, for centrifuge tubes, pipette tips, trays, beakers, or cylinders [10 – 13]. PP is made from propene through polymerization with specific catalysts. The polymer chain consists of a carbon backbone with alternating methyl- and hydrogen side groups [Fig. 3]

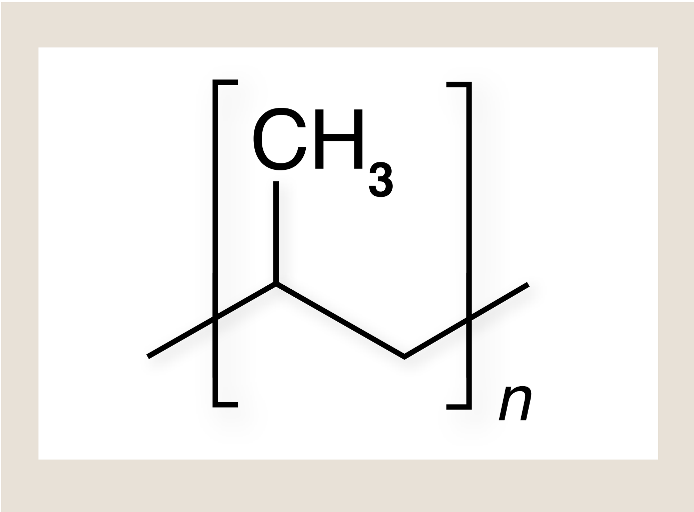

Fig. 3: The chemical structure of polypropene (PP)

Chemists differentiate between three types of polypropylene based on the orientation of the methyl group:

> The methyl group can be aligned on the same side of the polymer chain – this is called isotactic PP [Fig. 4a]
> The methyl group can be alternately aligned on the side of the polymer chain – this is then called syndiotactic PP [Fig. 4b]
> The methyl group can be randomly oriented –atactic PP [Fig. 4c].

The orientation of the methyl group is defined in the production process via the catalyst used [14], which has a significant impact on the properties of PP. The more regularly the methyl group is distributed, the better the crystallinity. Isotactic PP and syndiotactic PP have broad crystalline areas and, therefore, high melting temperatures around 160°C and even up to 180°C. In contrast, atactic PP is amorphous with lower melting temperatures and lower density. The properties of PP can be even more closely tailored to the desired application through the choice and design of the processing methods.

Isotactic PP is the most common type used in industry as it has the highest crystallinity and melting point of all variants. In practice, consumables made of PP can be used at 140°C for short periods and 100°C for long periods without losing their dimensional stability. Consequently, items made of PP can be autoclaved without problems, making this material valuable for sterile applications in the laboratory. PP is also physiologically harmless and without odor. Since PP is non-polar, you can use it for specific applications, such as molecular biology.

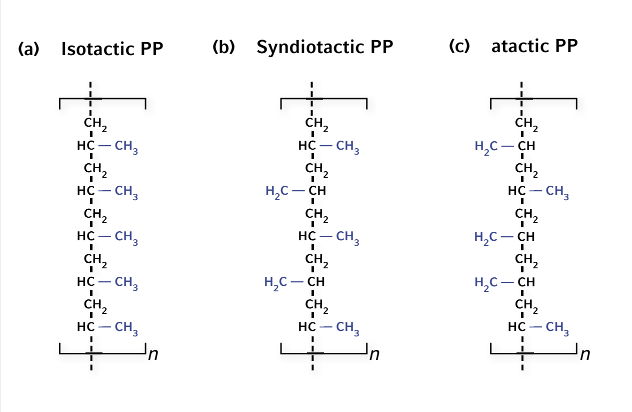

Fig.4: Different stereoisomers of polypropene (PP) [36]

Polypropene exhibits a higher temperature resistance than PE and is significantly stronger, stiffer, and harder. However, at low temperatures, PP quickly becomes brittle.

Finally, PP shows high resistance against aqueous solutions of salts, acids, and bases – even at higher temperatures and against most organic solvents and aliphatic hydrocarbons. Nevertheless, before using a specific solvent, you should check the chemical resistance of each consumable [15].

Again, PP is recyclable, especially when it is single-grade plastic. The recycling code for PP is #5. The energy demand for the production of 1 kg of polymer resin is high at 77.9 MJ but a little bit lower than that for the production of HDPE or LDPE. On the other hand, the energy content is slightly higher than of the PE-variants mentioned above, with 46.4 MJ instead of 34.0 and 36.7 MJ, respectively.

Polystyrene – not only for Styrofoam® boxes

Everybody knows the Styrofoam boxes that deliver cooled materials like enzymes or cells. Styrofoam is certainly the most known form of polystyrene (PS). But polystyrene is available in other shapes in the laboratory, e.g., as transparent culture flasks, tissue culture trays, petri dishes and microwell plates, as well as for medical applications, such as in diagnostic components [16-19].

The main building block of polystyrene is phenylethene, better known as styrene, which is generated through the dehydrogenation of ethylbenzene [Fig. 5]. There are several variants of PS, depending on the orientation of the phenyl

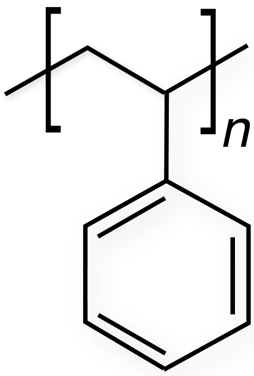

Fig. 5: The chemical structure of Polystyrene (PS)

group. The orientation of the phenyl group can be isotactic (on one side of the carbon backbone), syndiotactic (on alternating sides of the carbon backbone) or atactic with a random orientation. The commercially available polystyrene is atactic, and only specific applications use syndiotactic PS.

The chemical formula already shows the high importance of the large phenyl groups within the polystyrene polymer. These groups prevent the formation of crystalline-like, ordered structures and hinder the rotation of the polymer chains around the carbon-carbon bonds. The "classic" polystyrene, also known as General Purpose Polystyrene (GPPS), is therefore transparent due to this lack of crystallinity. It has high rigidity and is relatively brittle.

Further essential properties that are important for work in the laboratory, include UV- resistance as well as temperature and chemical resistance. When working with items made of PS, one has to be aware that PS is not UV-resistant and displays a relatively limited temperature resistance range of between -10°C and +70°C. While it is suitable for diluted acids and bases, you should not use polystyrene products with hydrocarbons or non-polar solvents, as the chemical resistance to the latter solvents is poor.

To overcome the weaknesses mentioned above, PS is often blended with 5-10% of butadiene rubber, which imparts higher impact resistance. This variant is known as High Impact Polystyrene (HIPS). Also, PS is often copolymerized with other monomers to improve its chemical resistance and heat- and UV stability. A further important feature to remember is the fact that PS is non-polar.

While it can easily be assumed that PS is hard to recycle, PS, with recycling code #6, can be recycled if it is properly sorted prior to collection. Such pure PS can be processed into regranulate by mechanical shredding, which can be further used to produce, for example, clothes hangers, furniture, or folding boxes. Most of the PS-waste in the private sector is mixed with other plastic waste and is incinerated. Separation and recycling are not rewarding for economic reasons. Incineration still yields 42.4 MJ per kg of polymer resin, but recycling is the better alternative. The industrial sector in Germany is an excellent example which shows that recycling is possible – here, about 64% of all Styrofoam packaging from industrial and commercial waste streams is recycled [20].

Besides mechanical recycling, new recycling methods like solvent recycling may help. The polystyrene waste is dissolved in a specific solvent, and insoluble impurities are separated. In a second step, the pure polystyrene is precipitated by adding a precipitating solvent. This technology is still in its infancy, and thus far, only two plants worldwide are using this process. The enormous energy demand of 82.8 MJ, and up to 87 MJ, to produce one kilogram of polystyrene resin clearly indicates that recycling has to be the solution of the future.

Polyethene terephthalate – better known as PET

Polyethene terephthalate (abbreviated as PET or PETE) is used in the laboratory mainly for lab bottles or culture flasks [21–25]. PET is made of terephthalic acid and ethylene glycol [Fig. 6]. The large aromatic ring of the terephthalic acid entity results in polymer chains with a straight and linear structure which, in turn, generate a polymer with notable stiffness and strength. Furthermore, PET is a very polar macromolecule with high intermolecular forces between the polymer chains but without any crosslinking of the individual polymer chains. PET forms semi-crystalline domains, but due to its slow crystallization rates, it is possible to influence whether semi-crystalline or amorphous PET is formed via the production process.

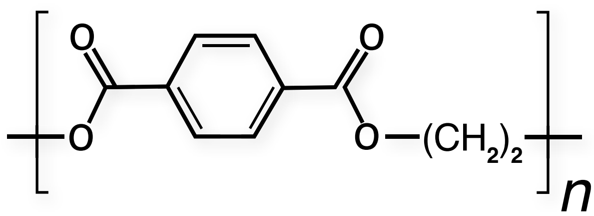

Fig. 6: The chemical structure of polyethene terephthalate (PET)

Semi-crystalline PET-C possesses high hardness and breaking strength, and the operating temperature range is between -20°C and +120°C, and even 200°C for short periods of time. PET-A, which stands for amorphous PET, is transparent (like PS) and impact resistant, but it is more temperature sensitive (-40°C to +60°C) and shows both lower hardness and stiffness than PET-C.

In general, PET is resistant to diluted acids, aliphatic as well as aromatic hydrocarbons, lubricants and alcohols, but not to halogenated hydrocarbons, bases or even hot water. In terms of re-usable or re-fillable lab products, PET is a challenging material that is generally only suitable for single-use material as it is not autoclavable.

In terms of recycling, PET is a pioneering material, which has been the most recycled plastic globally for years. Through recycling, part of the 71 MJ of primary energy needed to produce one kilogram of virgin PET can be saved, and in addition, less than the 2.19 kg of CO_2e released during the production will be emitted. PET has recycling code #1.

Polycarbonates – a versatile group of polymers

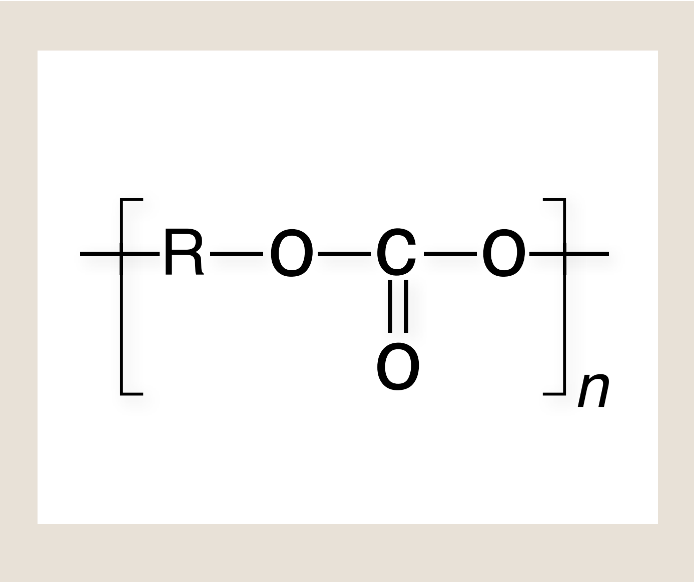

Fig. 7: The chemical structure of polycarbonate (PC)

Polycarbonates are a class of polymers with a carbonate group in their polymer chain, which explains the origin of their name [Fig.7]. The most widely used polycarbonate is made of bisphenol A and phosgene. Polycarbonates (PC) are used in the laboratory for various items including cell culture flasks, laboratory goggles and face shields, insert plates for cell culture, and even membrane filters [26-31].

Polycarbonates are widely used in the laboratory and in medical applications due to their biocompatibility. PC is also a strong, tough and durable material with high-impact resistance, exhibiting high rigidity. These properties vary between the different polycarbonates and are influenced by their structure and molecular mass. For example, the higher the molecular mass of a polycarbonate, the more rigid the polymer.

Polycarbonates can be made amorphous, resulting in an optically transparent material. Due to its high impact resistance and optical transparency, PC is a suitable replacement for glass and is used, for example, for safety glasses as well as for prescription eyeglass lenses. The only disadvantage is the low scratch resistance. Only items made of specific polycarbonate grades are used in medical applications or in the lab. They can be sterilized by gamma radiation, ethylene oxide, or autoclaving as PC is resistant to high temperatures above 120°C. Polycarbonates are also resistant to various chemicals like diluted acids, oils or ethanol, but not to bases, aromatic or halogenated hydrocarbons, ketones, and esters. Furthermore, you should not expose polystyrene products to hot water as this can result in stress cracks in the material.

Polycarbonate has a lot of advantages. Disadvantages, like its UV sensitivity, can be solved by adding specific stabilizers which render the material UV-resistant. But there's one disadvantage compared to all the other plastic materials presented above, which cannot be fixed by smart chemical modifications: PC is relatively expensive. In addition, its production is far more energy intensive than other plastics: it takes 104 MJ to produce one kilogram of PC polymer resin, and the process releases 3.4 kg of CO_2 equivalents. This is more than twice as much as is released in producing one kilogram of PP. Recycling is again one way to lower the carbon footprint. Pure polycarbonates can easily be recycled as they melt at higher temperatures without degradation – like all the other plastics mentioned above. The polymer can then be shaped into new forms by injection moulding. Advanced post-consumer waste recycling includes mechanical recycling or chemical recycling [32,33]. The recycling code for PC is #7.

All the major features of the materials mentioned above are summarized in table 1 to give you a quick overview for your daily lab work.

Plastic type	Temperature resistance	Autoclavable	Chemical resistant against*	Recycling code	Important features
PE	160° C to 180° C	yes	aqueous solutions of salts, acids and bases, most organic solvents and aliphatic hydrocarbons	#5	non-polar, brittle at lower tempera-tures
PE	105 to 115° C (LDPE) 120 to 130° C (HDPE)	no	diluted acids and bases, solents, alcohols or aliphatic hydrocarbons	#2 HDPE #4 LDPE	non-polar
PET	-20° C to 120° C (PET-C) -40° C to 60° C (PET-A)	no	diluted acids, aliphatic as well as aromatic hydrocarbons, lubi cantsor alcohols	#1	polar
PS	-10° C to 70° C	no	diluted acids and bases, not against hydrocarbons or non polar solvants	#6	non-polar, transparent
PC	-40° C to 130° C	yes	diluted acids, oils or ethanol, hot water can result in stress cracks	#7	polar, transparent

Table 1: Characteristic of plastic used in the lab

***Check out the cemical resistance for your application here:**
https://www.eppendorf.com/product-media/doc/en/114794_Userguide/Eppendorf_Consumables_User-guide_023_Tubes_Tips_Chemical-stability-consumables.pdf

https://www.kendrion.com/fileadmin/user_upload/Downloads/Datasheets_Operating_instructions/Valves_Fluid_Control/Chemical-resistance-valve-technology-Kendrion-EN.pdf

Recyclability and the carbon footprint

The production of plastics from crude oil is energy-intensive, with PC having the highest demand, PET the lowest and PP the second-lowest demand of energy for the manufacture of the respective polymer resin (table 2). At the same time, the global warming potential for the production of 1 kg of polymer resin is also the highest for PC and the second highest for PET, but the lowest for PP. The energy demand and global warming potential of LDPE and HDPE are found in between.

	Total primary energy demand to produce 1 kg of polymer resin [MJ]	Energy content in 1 kg of polymer resin (energy recovery potential) [MJ]	Global warming potential for production of 1 kg of polymer resin [kg CO_2e]
HDPE[1]	80.2	34.0	1.8
LDPE [1]	82.9	36.7	1.87
PP [1]	77.9	46.4	1.63
GPPS [1]	82.8	42.4	2.25
HIPS [1]	87	42.4	2.43
PET (bottle grade)[1]	71.2	24.0	2.19
PC [1]	104.3	33.0	3.4

Table 2: Overview on energy demands and CO_2-emissions to produce 1 kg of plastic resin from raw material extraction to polymer resin at plant and the energy content in 1 kg of polymer resin

All the data can be downloaded here:
https://plasticseurope.org/sustainability/circularity/life-cycle-thinking/eco-profiles-set/

In respect of the global warming potential, PP is the best choice. But to further lower the environmental impact of a product, it is necessary to look at its entire life cycle, which consists of the production phase, use phase and end of life. As the use phase in the lab often constitutes single-use, we must focus on the end of life. Here, recycling and re-entering the material is the best way to lower the environmental impact further. The plastics used in the lab are generally recyclable, and as most items are made of pure plastic without many additives or blends, they lend themselves well to the recycling process. Ideally, these plastics should be sorted according to type. But as most plasticware used in the laboratory is defined as being contaminated, it is difficult to return it to the waste stream due to legal restrictions and for health and safety reasons. The second best option today is to incinerate plastics. All plastics display a relatively good thermal value, except for PET (table 2). Again, PP shows the best value, followed by LDPE and HDPE. But burning plastics releases CO_2 into the atmosphere, which reinforces climate change. Research is already working on newer recycling options like the enzymatic degradation of, for example, PET [34] as well as chemical recycling of plastic waste [35]. But these options are still in the pilot phase.

What does this mean for the future? It is certain that plastics will not be replaced in the laboratory due to their unique properties that help ensure consistent and reliable experimental results. That being said, improvements will have to be made with respect to the switch from crude oil as a resource for plastic production to other renewable, bio-based resources, as well as recycling methods which will keep the material in the cycle, thus moving forward in the journey towards a real circular economy.

References

[1] https://www.eppendorf.com/product-media/doc/en/146279/Consumables_White-Paper_026_Consumables_Leachables-Minimizing-Influence-Plastic-Consumables-Laboratory-Workflows.pdf
[2] https://www.eppendorf.com/product-media/doc/en/625556/Consumables_Application-Note_417_Summary-Microcentrifuge-Tubes_Summary-Extractables-Leachables-Microcentrifuge-Tubes-Extensive-HPLC-GC-MS-Analysis.pdf
[3] https://www.britannica.com/science/polyethylene
[4] https://www.britannica.com/topic/industrial-polymers-468698#ref608620
[5] https://www.chemeurope.com/en/encyclopedia/Polyethylene.html
[6] https://www.kunststoffe.de/a/grundlagenartikel/polyethylen-pe-254120
[7] https://polymerdatabase.com/polymer%20classes/Polyolefin%20type.html
[8] https://www.kunststoffe.de/a/grundlagenartikel/chemikalienbestaendigkeit-von-polyethyle-260145
[9] https://www.umweltbundesamt.de/kunststoffe#hinweise-zum-recycling
[10] https://plasticseurope.org/sustainability/circularity/life-cycle-thinking/eco-profiles-set/
[11] https://www.britannica.com/science/polypropylene
[12] https://www.britannica.com/topic/industrial-polymers-468698/Polypropylene-PP#ref608634
[13] https://www.maschinenbau-wissen.de/skript3/werkstofftechnik/kunststoffe/351-polypropylen
[14] https://doi.org/10.3390/ma7075069
[15] https://www.eppendorf.com/product-media/doc/en/114794_Userguide/Eppendorf_Consumables_Userguide_023_Tubes_Tips_Chemical-stability-consumables.pdf
[16] https://www.kunststoffe.de/a/grundlagenartikel/polystyrol-ps-264382
[17] https://www.britannica.com/science/polystyrene
[18] https://www.britannica.com/topic/industrial-polymers-468698/Polypropylene-PP#ref608639
[19] https://polymerdatabase.com/polymer%20classes/Polystyrene%20type.html
[20] https://kunststoffverpackungen.de/wp-content/uploads/2022/02/Conversio-Report-IK-EPS-20022020.pdf
[21] https://www.britannica.com/science/polyethylene-terephthalate
[22] https://www.petrecycling.ch/de/wissen/wertstoff-pet/lexikon-der-kunststoffe
[23] https://www.chemie.de/lexikon/Polyethylenterephthalat.html
[24] https://www.kunststoffe.de/a/grundlagenartikel/polyethylenterephthalat-pet-285552
[25] https://www.maschinenbau-wissen.de/skript3/werkstofftechnik/kunststoffe/353-pet
[26] https://en.wikipedia.org/wiki/Polycarbonate
[27] https://www.kunststoffe.de/a/grundlagenartikel/polycarbonat-pc-285374
[28]https://www.maschinenbau-wissen.de/skript3/werkstofftechnik/kunststoffe/354-polycarbonat
[29] https://www.essentialchemicalindustry.org/polymers/polycarbonates.html
[30] https://www.chemie.de/lexikon/Polycarbonate.html
[31] https://ugplast-inc.com/recycling-solid-polycarbonate-sheets/
[32]https://solutions.covestro.com/de/highlights/artikel/stories/2019/polycarbonat-aus-recycelten-kunststoffen
[33]https://www.recycling-magazine.com/2021/08/05/sabic-to-launch-circular-polycarbonate-from-pcr/
[34] https://doi.org/10.3389%2Ffbioe.2021.771133
[35] https://handling-solutions.eppendorf.com/liquid-handling/sustainability/detailview/news/chemical-recycling-of-plastics-the-alternative-to-other-recycling-methods/
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