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Evaluating the recyclability and restabilization of laboratory plastics consumables: impact of autoclaving and mechanical recycling on polypropylene

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Laboratory environments generate substantial amounts of plastic waste primarily consisting of single-use polypropylene (PP) consumables such as pipette tips or test tubes. In this study, the recyclability of such materials is investigated with a focus on the influence of autoclaving and mechanical recycling. Further, restabilization strategies are evaluated for these materials. Virgin PP pipette tips and post-consumer laboratory PP recycle consisting of low melt viscosity PP are subjected to multiple extrusion cycles to simulate mechanical recycling. Autoclaving at 121 °C and elevated pressure for 20 min does not adversely affect the material's melt flow, tensile properties, or oxidative stability. This shows that decontamination by autoclaving does not impair recyclability. In contrast, reprocessing of the regenerate simulated through repeated extrusion causes pronounced aging particularly in post-consumer laboratory PP. To counteract these effects, different stabilizer formulations are tested, including a bio-based system containing an alditol and α -tocopherol. This formulation provides superior oxidative stability, consistent melt viscosity, and retention of mechanical properties compared to industrial reference stabilizer formulations. The results demonstrate that autoclaved laboratory PP can be successfully recycled by utilizing a suitable stabilization strategy. This enables a sustainable reuse of laboratory plastics in a second life cycle through effective recycling processes.

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Sustainability spotlight

This work addresses the growing challenge of plastic waste generated in laboratory environments by demonstrating that polypropylene (PP) consumables, such as pipette tips or test tubes, remain suitable for mechanical recycling after autoclave decontamination. Further, the results show that appropriate restabilization strategies enable a reliable second life cycle of the material. In particular, the use of bio-based antioxidant systems offers a more sustainable alternative to conventional stabilizer systems. The study aligns with SDG 12 by enabling the circular use of laboratory plastics, with SDG 9 through an industrially feasible mechanical recycling and restabilization pathway, and with SDG 13 by reducing CO₂-equivalent emissions that would otherwise arise from landfilling or incineration of the plastics waste.

1 Introduction

Laboratories in biological, chemical, pharmaceutical, and medical fields generate large amounts of plastic waste daily. Estimates suggest that approximately 5.5 million tons¹ of

laboratory plastic waste were produced in 2014, corresponding to about 1.5% of global plastic production.² This number has likely increased in recent years due to rising global plastics consumption. The waste comes from disposable materials such as pipette tips, microcentrifugation tubes, test tubes, reagent bottles, or Petri dishes, among others.^{3,4} Laboratory consumables are mostly made of polypropylene (PP) or polystyrene (PS) and are typically discarded after a single use.⁵ Recent analyses further show that laboratory consumables represent one of the largest sources of carbon emissions in science. Purchase-related emissions account for approximately 56% of total laboratory emissions, of which consumables contribute about 35%.⁶

Sustainable laboratory practices have therefore become increasingly important to reduce the environmental impact of

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research activities.^{7,8} In the context of sustainable resource management, strategies are commonly structured according to the waste hierarchy (reduce, reuse, recycle), where recycling is considered only after reduction and reuse options have been explored.^{9,10} In laboratory environments, reduction of plastic consumption and the reuse of laboratory consumables therefore represent important first steps toward more sustainable practices. Here, laboratory sustainability programs such as LEAF or My Green Lab can already help reduce emissions and promote sustainable practices in research environments.¹¹ However, reduction strategies are often limited in laboratory environments. Many laboratory consumables are designed for single use to ensure sterility, to avoid cross-contamination, and to comply with strict regulatory and quality requirements.¹² As a result, some approaches have shown feasibility to reduce, substitute or reuse articles, but eventually at the end of single-use articles' lifetime or where ever these approaches are not feasible, recycling remains a better option than incineration.^{10,13–15} The use of tip-washing systems is an option to reuse pipette tips in laboratory environments. These systems enable users to reuse pipette tips an average of 20 times, thereby helping to reduce plastic consumption.^{16,17} Many single use laboratory plastic articles have been shown to be easily reusable.¹³ Studies have demonstrated that pipette tips can be reused after appropriate washing or sterilization procedures without compromising analytical data quality.^{18,19} However, the applicability of such approaches strongly depends on the experimental context. Studies on autoclaving syringes revealed practical limitations after sterilization since remaining water droplets caused contamination and led to unfeasibility for their reuse.⁷ In addition, the sterilization and drying processes are associated with high water as well as energy consumption, but are still better in terms of emissions.¹³ Furthermore, such approaches may require substantial solvent use, particularly when ethanol is used for cleaning,⁷ and a significant capital investment for an additional laboratory apparatus. Even though reuse is the more desirable option, it becomes limited after multiple reuse cycles or in laboratories where it is not feasible due to sterility requirements. Mechanical recycling, by contrast, offers a straightforward alternative with several advantages, as it is not constrained by sterility requirements, enables the processing of a wide range of laboratory plastics (including PS), and can be implemented without additional investment in laboratory infrastructure.²⁰ Furthermore, it is easily scalable to high-throughput laboratory environments. Therefore, while reuse strategies can be effective in specific settings, mechanical recycling of laboratory waste represents a more broadly applicable alternative for reducing plastic waste in laboratory environments.

Driven by policy initiatives such as the European Green Deal²¹ and increasing pressure to implement sustainable practices in all sectors, recycling is becoming increasingly important. Regulatory frameworks such as the EU Circular Economy Action Plan²² call for innovative solutions to close material loops even in highly regulated environments like laboratories.²³ Given the growing global plastic waste problem and the limited capacity of landfills and incineration facilities, recycling

laboratory plastics is of great importance.^{24,25} Moreover, this waste stream represents a valuable recycling feedstock due to its clean composition and often high optical clarity. In order to facilitate recycling, PP and polystyrene (PS) waste can be collected separately in labs without much effort, so that mono-material plastic waste is obtained. However, the majority of this waste is currently subjected to thermal treatment or landfill disposal.^{26,27} A key aspect of laboratory plastic waste from biosafety level 1 and level 2 laboratories is its decontamination by autoclaving it (*i.e.*, under standardized conditions: 121 °C, 2 bar, 20 min),²⁸ after which it is disposed of as residual waste.²⁰ These conditions are used to ensure that biological residues are effectively decontaminated before disposal. We have recently developed a plastic waste collection scheme for life-science laboratories that enables their mechanical recycling and assessed the CO₂ equivalent emissions of the recycling of these lab plastics in comparison to incineration in a simplified life cycle assessment (LCA).²⁰

Both open-loop and closed-loop mechanical recycling approaches could be considered for these plastics. Closed-loop recycling, where materials are reused for their original purpose, is challenging primarily due to logistical and practical constraints.^{29–31} However, companies such as LabCycle manufacture laboratory consumables such as screw cap tubes, dosage cups, or Petri dishes out of laboratory waste targeting a closed-loop recycling strategy.³² While this pathway is promising, it is not universally applicable as many laboratories lack the required waste separation, decontamination infrastructure, or material consistency needed to enable a fully closed loop. Open-loop applications could offer a viable alternative.^{33,34} Recycled PP from laboratory waste exhibits a characteristically high melt flow, which makes it particularly suitable for certain applications. Such high melt flow recyclates can be used in the production of new laboratory items, thin-walled products, or in spinning processes, for instance in manufacturing of PP fibers.³⁵ Despite these promising applications, the use of recycled plastics remains subject to key limitations. Recycled plastics are generally affected by three major factors:³⁶

- (1) Degradation through processing, aging, or (photo) oxidation.
- (2) Polymer mixtures/blends.
- (3) Impurities or contaminants.

Predamage in polymers such as PP manifests itself in a reduction in molecular weight and an increase in carbonyl and acidic functional groups due to oxidative degradation processes.^{37,38} Changes in rheological and mechanical properties are further consequences.³⁹ To enable the sustainable reuse of laboratory plastics, restabilization of the material through suitable antioxidant formulations is mandatory.⁴⁰ The incorporation of antioxidants during the recycling process can mitigate these degradation effects by neutralizing free radicals and decomposing hydroperoxides formed during processing.^{41,42} Primary antioxidants such as sterically hindered phenols act as free radical scavengers while secondary antioxidants like phosphites decompose hydroperoxides.^{43,44} Synergistic antioxidant systems combining primary and secondary antioxidants are established widely in industry.^{45,46} Recent



studies showed that alditols as a bio-based alternative have antioxidant properties in combination with a primary antioxidant.^{47,48} While the mechanistic background of the antioxidative effect of alditols is a matter of research, they are considered as alternative stabilizers due to increasing ecological concerns associated with traditional phosphites and their oxidation products.^{49,50}

Various recycling approaches have been investigated for medical and laboratory-related plastics ranging from thermochemical processes such as steam cracking to CO₂-assisted pyrolysis.^{51,52} A recent study has also explored the recycling of PP face masks highlighting the increasing relevance of sustainable waste management in the medical sector.⁵³ In addition, solvent-based strategies have been proposed as an alternative for polyolefin purification and reuse.⁵⁴ While these approaches demonstrate promising pathways, they are energy-intensive and require complex infrastructure. In contrast, mechanical recycling and restabilization of laboratory-grade PP after autoclave decontamination remains largely unexplored. PS cell culture flasks were recently investigated as a model for laboratory plastic recycling. Sover *et al.* demonstrated that after autoclave decontamination, PS flasks can be mechanically recycled through shredding and injection molding without major loss in mechanical performance or melt flow behavior.⁵⁵ However, transparency and cell adhesion were reduced, limiting reuse for biological applications. Another study demonstrated that PP surgical wrapping paper from operating rooms can be recycled into new products with sufficient mechanical strength.⁵⁶ To the best of our knowledge, an open-loop recycling approach for laboratory-grade PP after decontamination by autoclaving and subsequent mechanical recycling with restabilization has only been scarcely investigated.⁵⁷

In the present work, the impact of autoclaving on two different types of PP laboratory plastics is investigated to assess potential recycling applications. Multiple extrusion cycles are used to simulate mechanical recycling and to evaluate material degradation. Autoclaved virgin pipette tips as well as commercially available recycle coming from post-consumer laboratory plastics are chosen as model systems. Additionally, stabilization strategies with phosphite-reduced additive systems are explored to improve material performance. Thermal analysis, melt flow as well as mechanical properties, rheology, and color characteristics were used to characterize degradation and stabilization efficiency.

2 Experimental

2.1 Materials

PP virgin pipette tips (PP VIR, TipOne pipette tip, 1250 μ L XL Graduated Tip, product number S1112-1020) were kindly supplied by Starlab GmbH and autoclaved afterwards. PP regranulate (PP REG) is composed of a heterogeneous mix of PP laboratory waste and was purchased from LabCycle Ltd. According to the supplier, PP REG consists of post-consumer laboratory PP sourced from biosafety level 1 and 2 laboratories. The waste stream primarily includes common consumables such as pipette tips, centrifuge tubes, and laboratory

containers which were autoclaved after use. Prior to the production of PP REG, the collected waste was pre-sorted by the manufacturer according to polymer type and color.

Calcium stearate (CS) was purchased from Baerlocher GmbH. Pentaerythritol tetrakis(3,5-di-*tert*-butyl-4-hydroxyhydrocinnamate) (Irganox 1010, AO-1) was provided by BASF SE. Tris(2,4-di-*tert*-butylphenyl)phosphite (ADEKA STAB 2112, PS-1) was kindly supplied by ADEKA Europe GmbH. RECYCLOBYK 4371 (BYK 4371) was provided by BYK-Chemie GmbH. (\pm)- α -Tocopherol (AO-2) was purchased from Alfa Aesar (purity \geq 97%). Mannitol (MAN) was delivered by VWR GmbH (purity \geq 98.5%). Unless otherwise stated, all chemicals were of industrial grade and all concentrations are given in % (w/w).

2.2 Autoclaving

Autoclaving was carried out on a VX-150 device from Systec (Linden, Germany). The temperature and pressure used in the autoclaving process over time are visualized in Fig. 1.

Starting from ambient temperature and pressure, saturated water vapor was generated within 10 min followed by pressurization to 100 kPa and heating to 120 $^{\circ}$ C within 10 min. This was followed by three pressure temperature cycles, during which the pressure was alternately increased to 200 kPa and reduced to approximately 110 kPa, while the temperature oscillated between 100 $^{\circ}$ C and 120 $^{\circ}$ C. Subsequently, the samples were held at constant conditions of 210 kPa and 120 $^{\circ}$ C for 20 min which corresponds to the actual sterilization process. Finally, the pressure was gradually reduced to ambient conditions and the temperature to 100 $^{\circ}$ C, after which the laboratory material was removed. The applied autoclaving conditions are known to achieve reliable decontamination of typical laboratory waste including biological residues.⁵⁸

2.3 Pre-processing of autoclaved materials

PP VIR was first coarsely ground using a cutting mill from Rapid (Bredaryd, Sweden). For the additive dosing system, PP VIR and PP REG were ground to a fine powder under liquid nitrogen on an ultra-centrifugal mill Retsch ZM 200 (Haan, Germany). The

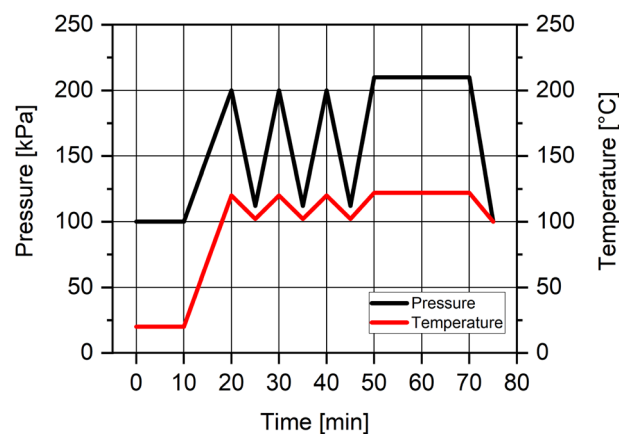


Fig. 1 Temperature and pressure used in the autoclaving program of the VX-150 systec device.



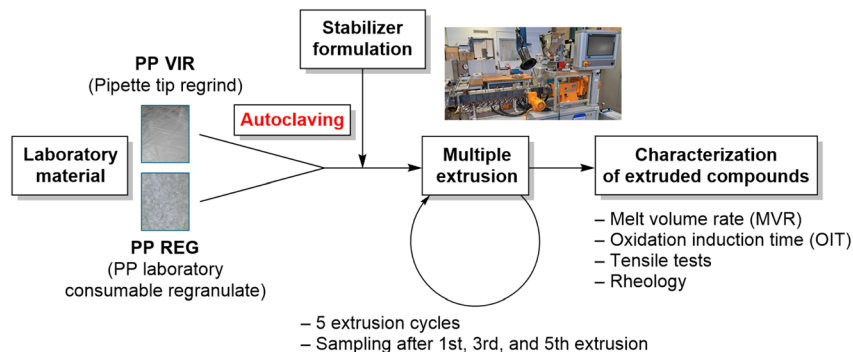


Fig. 2 Representation of the experimental working process of autoclaving, multiple extrusion, and analytics.

resulting powder was subsequently dried overnight at 70 °C *in vacuo* at 50 mbar (Fig. 2).

2.4 Material characterization

2.4.1 Differential scanning calorimetry. The presence of foreign polymers was investigated and determined by differential scanning calorimetry (DSC). DSC measurements were performed under nitrogen atmosphere (flow rate: 50 mL min⁻¹) on a Mettler Toledo DSC 822e (Columbus, Ohio, USA) device. DSC specimens were prepared by weighing in approximately 5 mg sample into a 40 µL standard aluminum crucible. The heating and cooling rates were 10 K min⁻¹ in a temperature range from -50 to 300 °C with evaluation based on the second heating cycle.

2.4.2 Oxidation induction time. To determine the thermo-oxidative stability of the substances and to estimate the content of phenolic antioxidants, the samples were investigated with a TGA-DSC 1 device from Mettler Toledo (Columbus, Ohio, USA). In the measurement procedure used, the substances were initially subjected to thermal pre-treatment (210 °C) under nitrogen atmosphere. After cooling to 120 °C, the sample was reheated to 210 °C. Following this, the atmosphere was switched from nitrogen to air. The maximum measurement duration was adjusted depending on the expected stability of the material to ensure that the oxidation onset was captured. All measurements were conducted in quintuplicate. The standard deviation was calculated based on the average of five independent measurements. Origin from OriginLab was utilized for data analysis.

2.4.3 Melt volume rate. The melt volume rate (MVR) was determined according to DIN EN ISO 1133-1. For PP, the standard conditions were 230 °C with 2.16 kg load. The dimension of the die was $L/D = 8 \text{ mm}/2.095 \text{ mm}$. Measurements were conducted in duplicate on a Göttfert MI-2 (Buchen, Germany) melt flow rate tester. For each measurement series, 25 values were recorded and the average was calculated. The standard deviations were determined based on these averages from both series.

2.4.4 Tensile testing. The mechanical properties of the samples were evaluated by tensile testing according to DIN EN ISO 527-1. Type 5A specimens were used for all tests produced on a BABYPLAST 6/10P (Kierspe, Germany) injection molding machine at 200 °C. Measurements were performed on a Zwick-Roell Z2.5 (Ulm, Germany) tensile testing machine equipped with

a 2.5 kN load cell and a mechanical extensometer. A test speed of 1 mm min⁻¹ was applied for determination of the tensile modulus, followed by 20 mm min⁻¹ for measuring tensile strength and elongation at break. A preload of 0.5 N was applied prior to each measurement. All tests were conducted under standard climate conditions according to DIN EN ISO 291 at 23 ± 2 °C and 50% relative humidity. Five specimens were tested per sample. Average values and standard deviations were calculated from all valid measurements using testXpert III software.

2.4.5 Gel permeation chromatography. Molecular masses and distributions were determined by high-temperature (HT) gel permeation chromatography (GPC). Analyses were performed using a PolymerChar (Valencia, Spain) GPC-IR, equipped with a 200 µL sample loop, at 160 °C. The mobile phase was 1,2,4-trichlorobenzene (TCB) containing 0.5 g L⁻¹ butylhydroxytoluene (BHT). The mobile phase flow rate was 1 mL min⁻¹. As a stationary phase, three Polymer Standards Service GmbH (PSS, Mainz, Germany) POLEFIN analytical linear XL columns (300 × 8.0 mm, L. × I. D.) with a matching precolumn (50 × 8.0 mm, L. × I. D.) were used. Detection was realized with a fixed wavelength IR detector (IR5, PolymerChar). The data were evaluated using PS calibration (EasiCal PS-1, Agilent, Waldbronn, Germany) and WinGPC software version 8 from Polymer Standards Service GmbH (Mainz, Germany). For each measurement, approximately 12 mg polymer was automatically mixed by the autosampler with 6 mL mobile phase. Simultaneously, the vials were flushed with nitrogen. Each sample was dissolved under shaking in the autosampler for 1 h at 160 °C before injection. Measurements were conducted in duplicate and the results were averaged and the standard deviation was determined.

2.4.6 Plate-plate rheometry. To investigate the viscoelastic behavior of the PP recyclates after multiple extrusion cycles, oscillatory shear rheological measurements on a Thermo Scientific HAAKE MARS III (Waltham, Massachusetts, USA) device were conducted using a plate-plate geometry. The measurements were carried out at 200 °C under nitrogen atmosphere to prevent thermo-oxidative degradation during the experiment. A parallel-plate geometry with a diameter of 35 mm and a gap of 0.75 mm was employed. The samples were compression-molded into discs at 170 °C for 10 min and placed onto the preheated lower plate of the rheometer. After complete melting (3 min), frequency sweeps were performed in the range



of 1 to 100 Hz at a constant strain within the linear viscoelastic region. All measurements were conducted in duplicate. The standard deviations were calculated based on the average of two independent measurements. Origin from OriginLab was utilized for data analysis.

2.4.7 Colorimetric analysis. Color measurements were performed using a BYK spectro-guide spectrophotometer (Geretsried, Germany) to evaluate the optical appearance of the injection-molded specimens. The measurements were conducted according to the CIELAB color space determining the color coordinates (L^* , a^* , b^*) as well as the gloss value (G). For each compound, nine individual measurements were carried out on three different tensile specimens (three measurements per specimen) to ensure statistical reliability. The average values and standard deviations were calculated from the nine measurements.

2.5 Implementation of multiple extrusion series

Following the working scheme (Fig. 2), PP was compounded on a Leistritz ZSE 18 MAXX (Nürnberg, Germany) parallel twin-screw extruder (Screw diameter: 18 mm, L/D screw ratio: 60). The multiple extrusion series were conducted at a throughput of 4.0 kg h⁻¹ at 300 rpm. The processing of PP was carried out using a maximum temperature of 230 °C. Prior to extrusion, the additives were premixed with finely ground PP powder and fed into the extruder *via* side feeding. The remaining material was introduced through the main feeder. Each compound was prepared at a batch size of 1500 g with 150 g of material sampled after the first, third, and fifth extrusion cycle. The formulation codes used are as follows:

STD: industrial standard formulation. COM: commercial state-of-the-art recycling formulation. F1: in-house developed formulation.

Table 1 gives an overview of all additive formulations that were tested in this work.

3 Results and discussion

3.1 Effect of autoclaving on material properties and recyclability

The material referred to as PP VIR corresponds to virgin PP pipette tips and is, therefore, free from foreign polymers (Fig. S1). PP REG, which was recovered from laboratory waste

was analyzed using DSC (Fig. S1). The results indicated that no other typical laboratory polymers such as polyethylene or polyethylene terephthalate were detected within the detection limit of approximately 1%. To evaluate the effect of repeated processing and autoclaving on the stability and mechanical performance of PP laboratory waste, OIT, MVR, and tensile properties were investigated. OIT provides information on the remaining content of primary antioxidants and the oxidative stability of the material which is critical for ensuring that the recyclate can withstand additional thermal processing steps without excessive oxidative degradation. It is defined as the time until the onset of oxidation under isothermal conditions under air atmosphere and is typically determined by DSC. MVR was determined to show changes in melt flow behavior due to thermo-mechanical degradation and is a highly relevant processing parameter particularly for applications involving melt shaping such as injection molding. It is measured by determining the volume of polymer melt that flows through a standardized capillary die under specified temperature and load within 10 min. Other characterization methods such as impact testing or long-term aging studies could provide additional information on toughness or durability. However, the employed methods were selected as they directly assess the most critical parameters for typical processing and application performance. Both autoclaving and mechanical recycling could be expected to promote polymer degradation, potentially reducing the residual antioxidant content, increasing melt flow, and impairing mechanical performance. This is especially important in second-life applications where variations in melt flow can significantly affect processability and part quality. Tensile tests were performed to evaluate the influence of autoclaving and reprocessing on the mechanical performance. They were conducted to assess whether the material retains sufficient strength, or stiffness for functional use in a second-life application. The results are presented in Fig. 3.

All PP grades in their as-delivered state showed low initial OIT values (≤ 6 min), indicating relatively low initial concentration of active phenolic stabilizer residues. A slight decrease in the OIT of the as-received PP VIR from 5.1 to 4.7 min was observed after autoclaving. However, the observed decrease is minor and given the typical variability of OIT measurements it cannot be unambiguously linked to the autoclaving step. The content of primary antioxidants in PP REG is particularly small (OIT = 2.1 min) suggesting a low residual antioxidant level and pre-damage of the material. High melt flow values of the PP grades in their as-delivered state were observed in MVR measurements where PP VIR shows an MVR value of 76 cm³/10 min. Usually, such very low-viscosity (low molecular weight) PP grades are optimized for rapid injection molding of thin-walled parts such as pipette tips. Typical PP grades used in injection molding often exhibit MVR values in the single-to low-double-digit range.⁵⁹ Autoclaving had no effect on the melt flow properties of PP VIR which is beneficial for processing as a consistent melt flow is crucial for reliable extrusion performance. The elevated MVR of the regranulated PP REG (110 cm³/10 min) compared to PP VIR is likely due to degradation during both the initial use phase and the recycling process as well as

Table 1 Overview of tested additive formulations, concentrations, and formulation codes used in the multiple extrusion experiments. All formulations contain a total additive concentration of 0.20% (w/w) and in addition 0.10% (w/w) CS. STD refers to an industrial standard formulation intended for virgin material, COM to a commercial state-of-the-art recycling formulation, and F1 to an in-house developed formulation

Formulation code	AO-1 [% (w/w)]	PS-1 [% (w/w)]	BYK 4371 [% (w/w)]	MAN [% (w/w)]	AO-2 [% (w/w)]
STD	0.1000	0.1000	—	—	—
COM	—	—	0.2000	—	—
F1	0.0750	0.0375	—	0.0750	0.0125



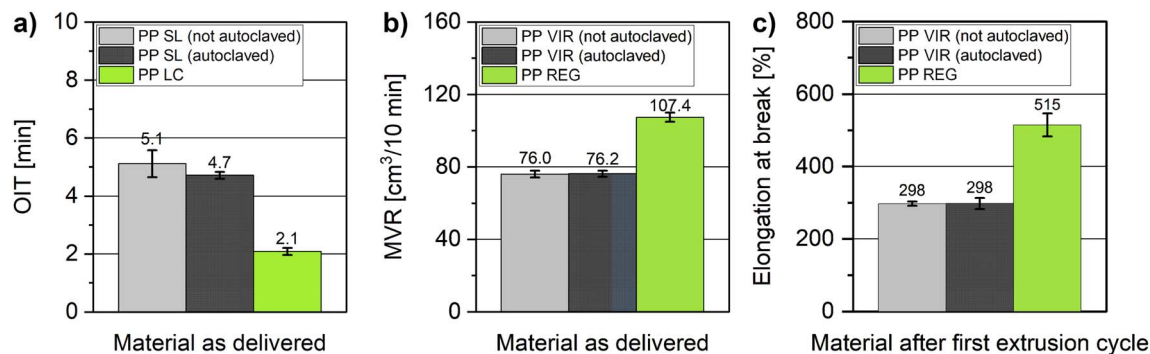


Fig. 3 Influence of autoclaving on the properties of PP grades in the as-received and autoclaved state. (a) OIT (210 °C, synthetic air) and (b) MVR (230 °C, 2.16 kg load) of PP VIR, PP VIR (autoclaved) and PP REG. (c) Elongation at break of PP grades was recorded after the first extrusion cycle since tensile test specimens could not be produced directly from the regrind. Values for MVR represent the mean of 2 measurements \pm standard deviation, while OIT and elongation at break are based on 5 measurements \pm standard deviation.

inherent material differences since PP REG consists of a heterogeneous mix of pipette waste. Mechanical properties of PP VIR remained unchanged after autoclaving which is consistent with the negligible change in MVR. The elongation at break stayed nearly constant at around 300%. In contrast, PP REG exhibited a higher elongation at break of more than 500% and lower yield tensile strength (Fig. S2).

In a further step, the number-average molecular weight (M_n), the weight-average molecular weight (M_w), and the dispersity (D) of the materials were determined to obtain a fundamental characterization of PP VIR and PP REG. Molecular weight distributions are shown in Fig. S3. The results are shown in Table 2.

The virgin material PP VIR exhibits higher molecular weight than PP REG, which is consistent with the increased MVR observed for PP REG. Autoclaving of PP VIR does not notably affect the molecular weight and its distribution in PP VIR as all values remain within experimental uncertainty. Although PP REG shows a significantly higher MVR than PP VIR (Fig. 3), the molecular weights and their distributions (Table 2 and Fig. S3) lie very close to each other. This is expected, because the melt viscosity and therefore the MVR is highly sensitive to even small changes in molecular weight. In this regime, minor reductions in chain length can already cause disproportionately large increases in flowability.⁶⁰

To evaluate the recyclability of pipette tip waste before and after autoclaving, materials were processed in multiple extrusion series to simulate mechanical recycling with subsequent analysis of the materials. OIT and elongation at break after five extrusion cycles as well as the MVR behavior during multiple processing are presented in Fig. 4.

All PP materials undergo a decrease in OIT during multiple extrusion cycles. In the case of PP VIR grades, the OIT halved

after five extrusion cycles indicating substantial stabilizer consumption during processing. For PP REG, the OIT showed only a slight decrease from 2.1 to 1.7 min after five extrusion cycles. This limited change implies that the material was already largely depleted of stabilizers prior to processing. In both cases, the melt flow increases from 76 to about 110 cm³/10 min over five extrusion cycles. This increase in MVR is attributed to chain scission occurring during processing.⁶¹ Autoclaving of PP VIR does not greatly affect the recyclability, as both autoclaved and non-autoclaved samples show a similar trend in MVR increase with the number of extrusions. The result indicates that the decontamination step does not significantly accelerate degradation or impair melt processing behavior. It is also in accordance with the respective OIT results. The MVR of PP REG increases from 107 to nearly 200 cm³/10 min in five processing iterations and is thus significantly higher compared to PP VIR. This pronounced increase suggests a greater extent of polymer degradation in PP REG, likely due to its lower initial thermal stability and oxidation resistance. Only minor changes were observed in the elongation at break for PP VIR (282%) compared to the initial state (298%). However, PP REG reveals a loss of 30% in elongation at break from its initial value of 515%, suggesting decreasing ductility after five extrusion cycles as already indicated by changes in MVR. The elastic modulus as a relevant parameter for laboratory consumables showed only negligible changes for both materials after autoclaving as well as after multiple processing over five extrusion cycles, indicating that the stiffness of the materials is largely retained (Table S1).

While the applied autoclaving program reflects common laboratory practice, real conditions may vary in cycle duration, temperature profiles, drying steps, and repeated sterilization. The negligible changes in the properties of PP VIR indicate that

Table 2 M_n , M_w , and D of PP laboratory consumables determined via GPC. Values are averages of 2 measurements \pm standard deviation

Sample	M_n [10^4 g mol ⁻¹]	M_w [10^5 g mol ⁻¹]	D
PP VIR (not autoclaved)	3.27 \pm 0.04	1.84 \pm 0.00	5.62 \pm 0.06
PP VIR (autoclaved)	3.16 \pm 0.06	1.83 \pm 0.01	5.81 \pm 0.09
PP REG	2.92 \pm 0.11	1.73 \pm 0.00	5.94 \pm 0.23



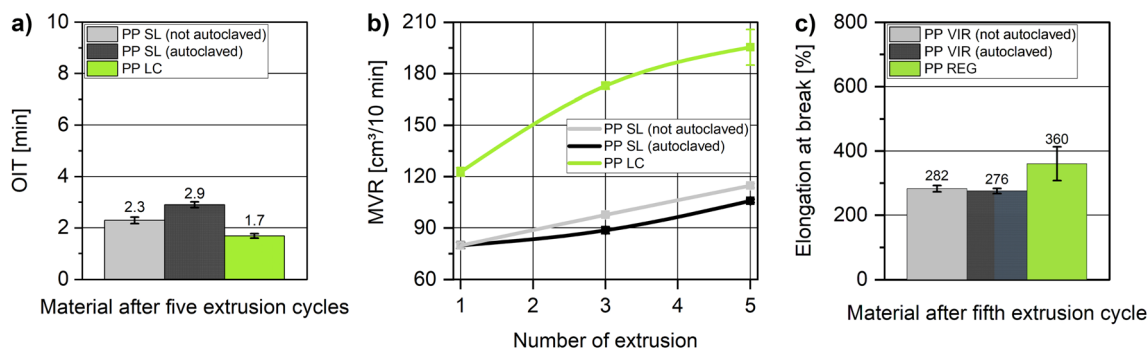


Fig. 4 Influence of multiple extrusion on the properties of PP grades in the as-received and autoclaved state. (a) OIT (210 °C, synthetic air) of PP VIR, PP VIR (autoclaved), and PP REG after five extrusion cycles. (b) MVR (230 °C, 2.16 kg load) of PP grades after first, third, and fifth extrusion cycle. (c) Elongation at break PP grades after five extrusion cycles. Values for MVR represent the mean of 2 measurements \pm standard deviation, while OIT and elongation at break are based on 5 measurements \pm standard deviation. Several error bars are too small for representation.

PP is largely resistant under standard conditions. However, harsher or repeated cycles may promote thermo-oxidative degradation and stabilizer depletion.⁵⁷ Therefore, the conclusions are robust for typical sterilization protocols but may not fully extend to more intense conditions.

3.2 Restabilization concept for a new life cycle

To enable the reuse of recycled PP from laboratory waste in new applications, restoring sufficient thermo-mechanical stability during reprocessing is essential, particularly in open-loop recycling pathways. As demonstrated in the previous section, especially PP REG shows clear signs of degradation due to prior use and reprocessing. Therefore, this section explores a tailored restabilization strategy using bio-based antioxidant systems in comparison to established industrial products as well as state-of-the-art recycling stabilizers. In-house studies showed that the stabilizer combination F1 (Table 1) consisting of conventional and bio-based (alditol and α -tocopherol) components performed well in terms of stabilization.^{47,48,62} Here, its performance in PP recyclates is evaluated. To determine the aging state and the efficiency of stabilization after multiple extrusions, the materials were analyzed with respect to their molecular properties and their mechanical performance. Table 3 presents the OIT values obtained after five extrusion cycles which were measured to evaluate the oxidative stability.

The oxidative stability was strongly enhanced by the addition of stabilizers. While the unstabilized materials showed very low OIT values below 3 min, an industrial standard stabilizer

Table 3 OIT of PP samples with different stabilizer formulations after the fifth extrusion cycle. Measurements were conducted at 210 °C under synthetic air. Samples were compounded with 0.20% (w/w) stabilizer. Values are averages of 5 measurements \pm standard deviation

Formulation	OIT [min]	
	PP VIR (autoclaved)	PP REG
—	2.9 \pm 0.1	2.2 \pm 0.4
STD	33.5 \pm 5.7	7.6 \pm 0.3
COM	14.2 \pm 1.3	7.5 \pm 1.1
F1	132.5 \pm 3.8	14.0 \pm 1.9

formulation STD provided effective protection in PP VIR but only moderate stabilization in PP REG. The addition of a commercial stabilizer system COM resulted in low OIT values for both materials. For PP VIR, STD was much more effective than COM while the effectivity of both stabilizer systems in PP REG was low. The bio-based formulation F1 exhibited by far the highest OIT in PP VIR exceeding 130 min and also provided the most efficient stabilization in PP REG. However, the general overall oxidation induction times in PP REG are low even in presence of 0.20% (w/w) antioxidants likely due to pre-existing oxidation that accelerates stabilizer consumption and oxidation onset. The OIT of typical virgin industrial PP grades is generally above 20 min, depending on stabilizer system, test conditions, and intended application.^{63–66} Ideally, PP recyclates should also exhibit OIT values within this range.

Fig. 5 shows the MVR change of PP VIR and PP REG over five extrusion cycles.

All stabilized samples showed a significant retention of melt flow properties. Further, the tested formulations maintained the MVR for PP VIR at nearly constant levels. In the case of PP VIR, the bio-based system F1 performed particularly well as the MVR remained almost constant at around 71 cm³/10 min over all extrusion cycles. This retention of MVR is highly relevant for processing since it ensures consistent viscosity during extrusion and injection molding.⁶⁷ For PP REG, the MVR increased slightly even in the presence of stabilization despite the addition of stabilizers, which is consistent with the low OIT values observed, as both measurements reflect ongoing chain scission and insufficient oxidative stability.

Mechanical properties of the recycled laboratory material were evaluated *via* elongation at break after the first and fifth extrusion cycle. Elongation at break was used as a measure for the ductility of the material and the preservation of molecular integrity since chain scission and oxidative degradation processes typically result in reduced elongation values. The results are presented in Fig. 6. Further, the yield tensile strength was measured. The corresponding data are provided in Fig. S4. However, only minor differences were observed between the compounds.

For PP VIR, elongation decreased slightly after multiple extrusion series and all stabilizers provided a comparable level



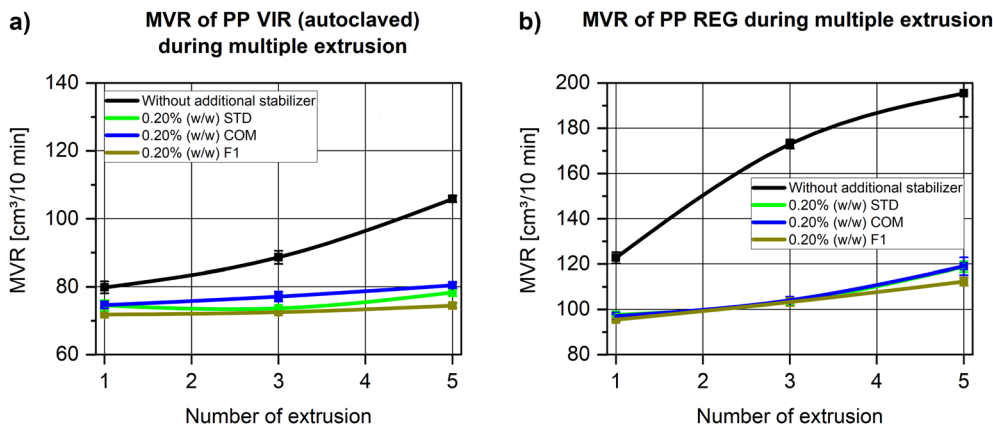


Fig. 5 Effect of different stabilizer systems on the MVR of different PP grades during multiple extrusion. MVR of (a) PP VIR (autoclaved) and of (b) PP REG over five extrusion cycles. The green curve lies beneath the blue curve and is therefore barely visible in plot b). Measurements were conducted at 230 °C using a 2.16 kg load. Values are averages of 2 measurements \pm standard deviation. Several error bars are too small for representation. STD: industrial standard formulation; COM commercial state-of-the-art recycling formulation; F1: in-house developed formulation with 0.0750% (w/w) AO-1, 0.0375% (w/w) PS-1, 0.0750% (w/w) MAN, and 0.0125% (w/w) AO-2.

of protection. In contrast, PP REG exhibited significantly higher initial elongation at break but also a stronger decline (30% from the initial value) in the unstabilized sample after five extrusions. Here, the bio-based system F1 outperformed the reference stabilizers. With the bio-based stabilizers, almost no change was observed in mechanical properties even after five extrusion cycles, demonstrating a good stabilization efficiency.

To further gain insights into molecular changes, oscillatory rheology was measured. Cross-over frequency is influenced by the molecular weight and is therefore plotted over the number of conducted extrusion cycles. Additionally, the complex viscosity as a function of the frequency is shown after five extrusion cycles. The results are presented in Fig. 7.

The cross-over frequency shifted to higher frequencies for unstabilized PP VIR and PP REG over repeated extrusions indicating a reduction of the average relaxation time, which is

consistent with a loss of molar mass. For PP REG without additional stabilizer, no cross-over was observed in the measured frequency range. Samples containing the reference and industry standard stabilizers, or the bio-based stabilizer system F1 showed only minor shifts in cross-over frequency, proving the excellent maintenance of molecular weight and molecular weight distribution. This shows that the stabilizer systems effectively protect PP from degradation and maintain its processing performance over multiple extrusion cycles. For PP VIR, stabilized samples exhibited a slightly higher complex viscosity after five extrusion cycles. In contrast, stabilizer in PP REG showed a more pronounced effect. The unstabilized sample displayed a significantly lower complex viscosity whereas the stabilized samples retained high viscosity levels. This indicates that the applied stabilizers were more effective in preserving the melt viscosity of PP REG during multiple

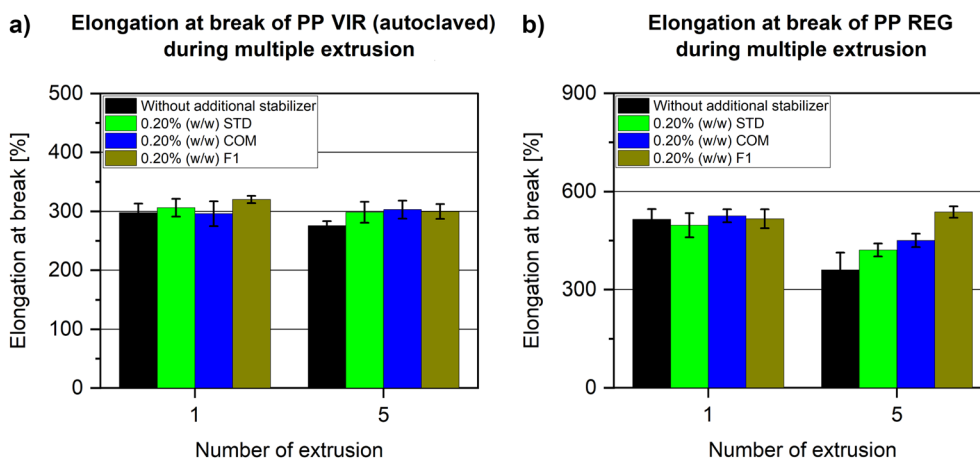


Fig. 6 Effect of different stabilizer systems on the elongation at break of different PP grades after one and five extrusion cycles. Elongation at break of (a) PP VIR (autoclaved) and of (b) PP REG after first and fifth extrusion cycle. Values are averages of 5 measurements \pm standard deviation. STD: industrial standard formulation; COM commercial state-of-the-art recycling formulation; F1: in-house developed formulation with 0.0750% (w/w) AO-1, 0.0375% (w/w) PS-1, 0.0750% (w/w) MAN, and 0.0125% (w/w) AO-2.



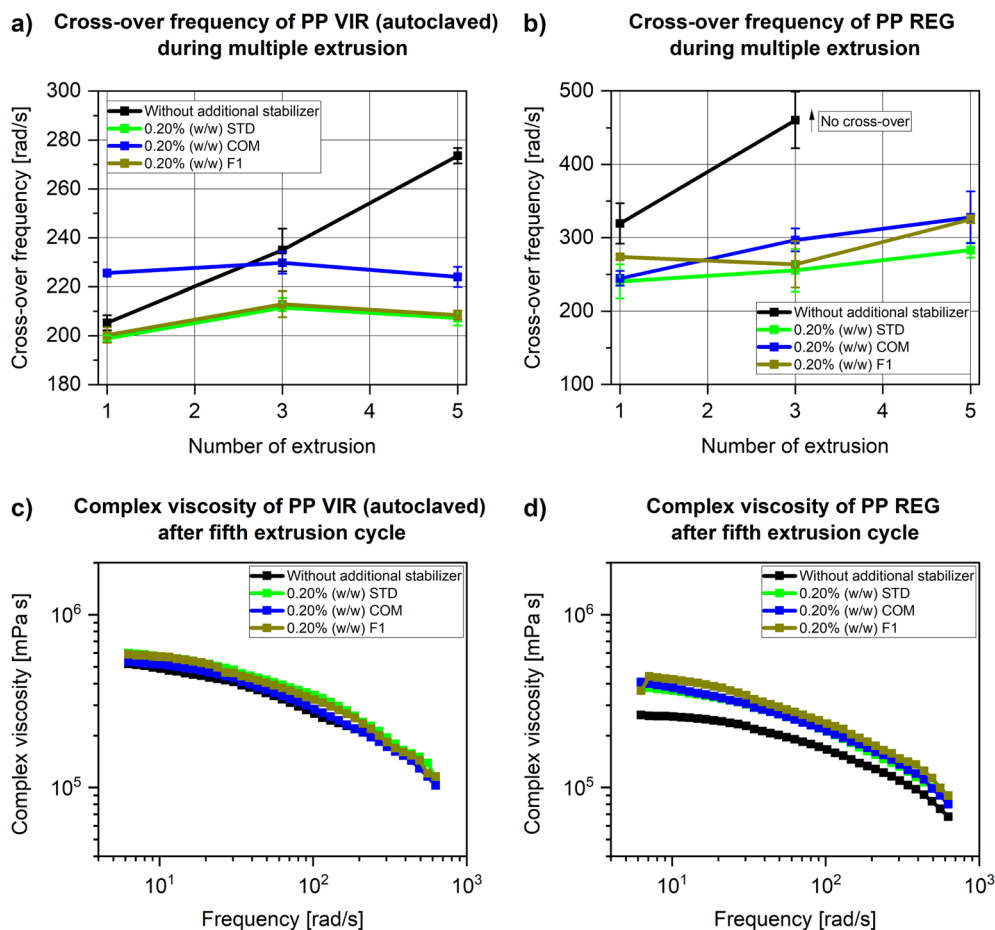


Fig. 7 Effect of different stabilizer systems on the cross-over frequency and complex viscosity of different PP grades. Cross-over frequency of (a) PP VIR (autoclaved) and of (b) PP REG over five extrusion cycles. For PP REG without additional stabilizer, no cross-over was observed in the measured frequency range. Complex viscosity as a function of frequency of (c) PP VIR and of (d) PP REG after five extrusion cycles. Values are averages of 2 measurements \pm standard deviation. STD: industrial standard formulation; COM commercial state-of-the-art recycling formulation; F1: in-house developed formulation with 0.0750% (w/w) AO-1, 0.0375% (w/w) PS-1, 0.0750% (w/w) MAN, and 0.0125% (w/w) AO-2.

extrusion cycles compared to PP VIR, and the result is in accordance with MVR observations.

The different behavior of PP REG compared to PP VIR requires further consideration. While autoclaving was shown to have negligible impact on material properties, PP REG exhibits significantly higher melt flow, lower oxidative stability, and stronger degradation during reprocessing. This behavior is attributed to the history of PP REG as a post-consumer recycle. In contrast to PP VIR, the material has already undergone application-related aging and (at least) one recycling step. These prior thermo-mechanical exposures likely resulted in partial depletion of stabilizers and the accumulation of oxidation products such as hydroperoxides.^{68,69} In addition, PP REG originates from a heterogeneous waste stream of laboratory consumables. Although no foreign polymers were detected by DSC (Fig. S1), variations in molecular weight distribution, additive content, and processing history are expected. Such heterogeneity can further have a negative impact on mechanical properties and can reduce the effectiveness of stabilization.³⁶ The inferior performance of PP REG is therefore not unexpected but rather characteristic for post-consumer PP recycles. In

particular, the low initial OIT values indicate that the material is already largely depleted of stabilizers prior to reprocessing and explains why further stabilization is less effective compared to PP VIR. Stabilizers added during reprocessing must first compensate for existing oxidative species and degradation products which accelerates their consumption and limits their protective effect. Nevertheless, the material still shows sufficient processability and mechanical performance for certain applications especially when appropriate stabilization systems are applied.

From an energy and climate perspective, mechanical recycling of PP is generally associated with lower energy demand and greenhouse gas emissions compared to virgin polymer production.^{70,71} Energy-intensive steps such as monomer synthesis and polymerization are avoided by mechanical recycling. In comparison to reuse systems, recycling does require remelting and reprocessing. However, it avoids additional water consumption, drying steps, and the use of cleaning agents, which can be of substantial amount depending on the application. In contrast, pathways such as incineration lead to a loss of material value and are associated with higher CO₂ emissions



despite partial energy recovery.⁷² Although a detailed life cycle assessment is beyond the scope of this study, the presented recycling and restabilization approach is expected to provide a favorable balance between resource efficiency, energy demand, and material performance.

3.3 Color stability and yellowness index

In addition to the thermal and mechanical properties, the optical appearance of the recycled materials is a crucial property especially for transparent applications where color deviations are easily visible. To assess such optical changes, the yellowness index (YI) of the injection-molded specimens was determined to evaluate color changes induced by thermo-mechanical degradation. Furthermore, the color coordinates (L^* , a^* , and b^*) of the Commission Internationale de l'Eclairage (CIE) L^* , a^* , and b^* color space and the gloss value (G) were measured. L^* is the lightness, and a^* and b^* represent the red/green and yellow/blue coordinates, respectively (Tables S2 to S5). The YI values after the first and the fifth extrusion cycle are shown in Table 4 while Fig. S5 shows a photograph of the tensile test specimens.

Autoclaving did not adversely affect the color stability of PP VIR. PP REG showed a slightly higher YI compared to PP VIR, which was also visually evident from a faint greenish tint. The YI increased with the number of extrusion cycles for all samples showing thermo-mechanical degradation and the formation of chromophoric oxidation products.⁷³ Among the additive formulations, STD and COM provided the best color stability for both PP VIR and PP REG, which showed only minor YI increases after five extrusions. In contrast, the samples that were stabilized with F1 exhibited pronounced yellowing, which can be attributed to chromophoric oxidation products derived from α -tocopherol during processing. This discoloration is consistent with the intrinsic yellowish hue of α -tocopherol itself and the formation of various degradation products including oxidized species, dimers, and trimers which act as chromophores contributing to visible color change.^{74,75} Overall, the results demonstrate that industrial established additive formulations

can effectively mitigate color changes during multiple recycling cycles. Nevertheless, the use of α -tocopherol may still be advantageous in recycled polyolefin grades that are commonly colored, such as black, red, or other dark-colored products, where the yellowing is masked and does not affect visual appearance.⁶² In contrast, for products that require high color purity such as transparent or white products, including cosmetic containers or medical components, the discoloration induced by F1 would be problematic and would render the recyclates less suitable. This differentiation provides practical guidance for implementing F1 in recycled polyolefins depending on end-use color requirements.

4 Conclusions

The present work demonstrates that the decontamination of laboratory waste such as pipette tips or test tubes through autoclaving does not impair the recyclability and properties of PP consumables. Further, it demonstrates that PP laboratory consumables consisting of high melt volume rate polymers can be effectively recycled when an appropriate stabilization strategy is applied. Key findings using comprehensive characterization including melt volume rate measurements, tensile testing, and oxidative stability analysis show that autoclaving at elevated temperature and pressure had no effect on material properties. However, mechanical recycling leads to a deterioration of material performance. A novel bio-based stabilizer system based on an alditol and α -tocopherol ensures superior retention of material properties compared to conventional products, although with the disadvantage of causing slight discoloration of the recyclates. These findings highlight the potential for a sustainable second life cycle of laboratory plastics and also provide a foundation for circular material use in scientific environments. Future investigations could further explore long-term stabilization and other application fields such as spinning processes for PP fibres. All in all, the results demonstrate that autoclaved laboratory PP can be successfully recycled utilizing an adequate stabilization strategy, which enables a sustainable and circular material use of laboratory plastics.

Author contributions

Kim Hao Ng: conceptualization, methodology, investigation, formal analysis, data curation, writing – original draft, visualization. Leonard D. Süß: investigation, writing – review & editing, visualization. Franziska Hirschel: investigation. Michael Müller: investigation, writing – review & editing. Bianca R. Schell: writing – review & editing, conceptualization. Elke Metzsch-Zilligen: project administration, funding acquisition, resources. Rudolf Pfaendner: writing – review & editing, conceptualization, supervision. Nico Bruns: supervision, resources, writing – review & editing, conceptualization.

Conflicts of interest

There are no conflicts of interest to declare.

Table 4 Yellowness index of PP VIR and PP REG after first and fifth extrusion. Since tensile test specimens of PP VIR could not be produced directly from the regrind and the irregular shape strongly affects YI measurements, a direct comparison was not meaningful. Samples were compounded with 0.20% (w/w) stabilizer. Values are averages of 9 measurements \pm standard deviation

Sample	Formulation	YI	
		1st	5th
PP VIR (not autoclaved)	—	7.0 \pm 0.3	15.2 \pm 0.4
PP VIR (autoclaved)	—	7.0 \pm 0.6	12.6 \pm 0.5
	STD	4.9 \pm 0.7	11.3 \pm 0.8
	COM	6.4 \pm 0.2	11.0 \pm 0.5
	F1	16.1 \pm 1.2	24.9 \pm 1.8
PP REG	—	8.4 \pm 0.5	12.5 \pm 0.2
	STD	7.7 \pm 1.1	19.4 \pm 2.0
	COM	6.3 \pm 0.7	10.3 \pm 0.5
	F1	12.3 \pm 0.3	17.6 \pm 3.2



Data availability

Additional data are provided in the supplementary information (SI). The data that support the findings of this study, including DSC, OIT, MVR, tensile testing, GPC, rheological, and colorimetric data, are available from Zenodo at <https://doi.org/10.5281/zenodo.18457708>. Supplementary information is available. See DOI: <https://doi.org/10.1039/d6su00069j>.

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