Closing the PET loop

What are the long-term prospects for recycled PET in beverage bottles?

November 2024

sus.lab
Sustainability in Business Lab

ETH zürich



Team at sus.lab



Sophie Führer
Author
Project Manager



Gabriela Vojtova
Author
Project Assistant



Julia Bachmann
Supervision
Co-Lead at sus.lab



Prof. Catharina Bening
Supervision
Head Circular Economy research at SusTec

Sus.lab is a “think-and-do-tank” of intrinsically motivated people with diverse backgrounds in engineering, science, management consulting, and entrepreneurship. Our mission is to drive the transition towards a net-zero and circular economy in collaboration with industry, policy makers, and academia. As part of the Group for Sustainability and Technology (SusTec) within the Department of Management, Technology, and Economics of ETH Zurich, our work bridges the gap between the latest academic research and industrial applications.

sus.lab

sus.lab Sustainability in Business Lab | ETH zürich

Disclaimer

The findings of this report result from a combination of literature review, market analysis, and stakeholder interviews. The conclusions are based on the PET recycling system within the Swiss context, and generalizations must be made with caution.

It is important to recognize that opinions expressed in this report are subject to change based on evolving circumstances, new insights, and differing viewpoints. Readers are encouraged to exercise critical thinking when assessing the complexities of recycled PET in beverage bottles.

Acknowledgements:

We express our sincere gratitude to Coca-Cola HBC Switzerland and PRS PET-Recycling Switzerland for their financial support of this study, as well as vital data contributions and active participation in discussions, which were integral to the project's success. We also extend our appreciation to the interview partners for sharing their expertise and offering insights that significantly informed this report.

Executive summary

Status quo of PET recycling in Switzerland and Europe

A significant increase in recycled output of polyethylene terephthalate (PET) is needed to satisfy the European Union's targets, and pledged volumes for recycled PET content in beverage bottles. In Switzerland, brands are making ambitious commitments about the recycled PET content in PET beverage bottles, many having committed to shift to 100% recycled PET. According to a Carbotech study, in 2020, the Swiss PET recycling system saved up to 2.65 t of CO_2-eq per tonne of collected goods compared to no recycling. In 2023, 84% of PET bottles in circulation were recycled, driving the production of recycled PET.

Limitations of 100% recycled PET in bottles

In the long run, implementing 100% recycled PET across the Swiss market is currently not feasible due to limited supply and material degradation. Recycled PET is in limited supply due to material loss during recycling and demand from other markets. From collection to output, the PET recycling process experiences material losses, preventing the implementation of 100% recycled PET content in beverage bottles across the Swiss market. Additionally, the demand for recycled PET from end markets other than PET beverage bottles could reduce the supply available for bottle-to-bottle production. Furthermore, PET cannot be recycled indefinitely due to material degradation with each recycling cycle. Repeated recycling can lead to contaminant accumulation, as well as changes in optical and mechanical properties. Particle contamination in bottles rises with increasing recycled PET content. Unwanted color changes in beverage bottles increase with recycled PET content but can potentially be mitigated by using high-quality PET material and additives. However, the effects of additives in recycled PET production over multiple cycles, including potential health and safety risks, are not yet fully understood and continue to be studied. Repeated mechanical recycling also decreases PET's molecular weight, which can negatively impact the bottle's mechanical properties (e.g., impact resistance). Solid-state polycondensation manipulation can be used to limit the negative effects of repeated PET mechanical recycling on the bottle's mechanical properties. Given today's technology, supply, and demand, individual beverage bottles with 100% recycled PET content are possible but on a system level the recommended threshold for recycled PET content in beverage bottles is 75 to 80%.

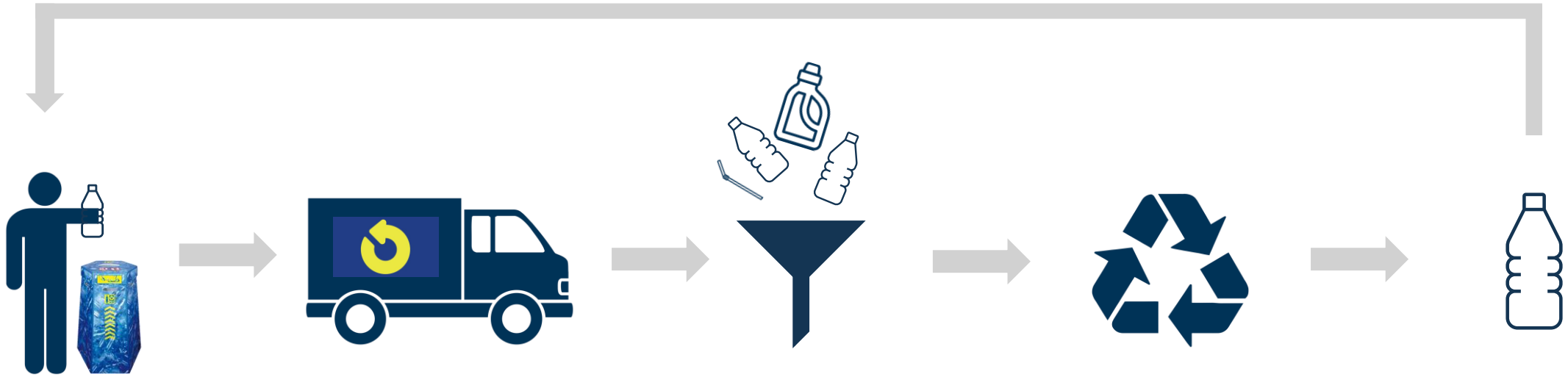
Prospects for PET recycling in Switzerland

A range of strategies exists to continuously improve PET recycling and increase the recycled PET content in beverage bottles, including developments in mechanical recycling technologies, investments in chemical recycling technologies, and utilization of additives. Mechanical recycling is the most widely spread PET recycling method, and it is here to stay. Investments in mechanical recycling technologies are essential to reduce material loss and degradation. As opposed to mechanical recycling, chemical recycling can depolymerize PET polymer into its monomers and potentially restore the material's virgin-like properties. While chemical recycling offers many benefits, further investment and technological advancements are needed to make it a commercially viable PET recycling method. Lastly, additives are intentionally added substances that can be used to prevent and/or reverse PET degradation. However, the use of additives and other chemicals should be approached cautiously, as they may pose safety and health risks.

Table of content

Status quo of PET recycling in Switzerland and Europe		**05-09**
Limitations of 100% recycled PET in bottles	Limited supply	**11-20**
	Material degradation	
Prospects for PET recycling in Switzerland	Mechanical recycling	**22-30**
	Chemical recycling	
	Additives	

Status quo | **The Swiss PET recycling system, PET-Recycling Schweiz, produces high-quality recycled PET material and supplies it back to the market**

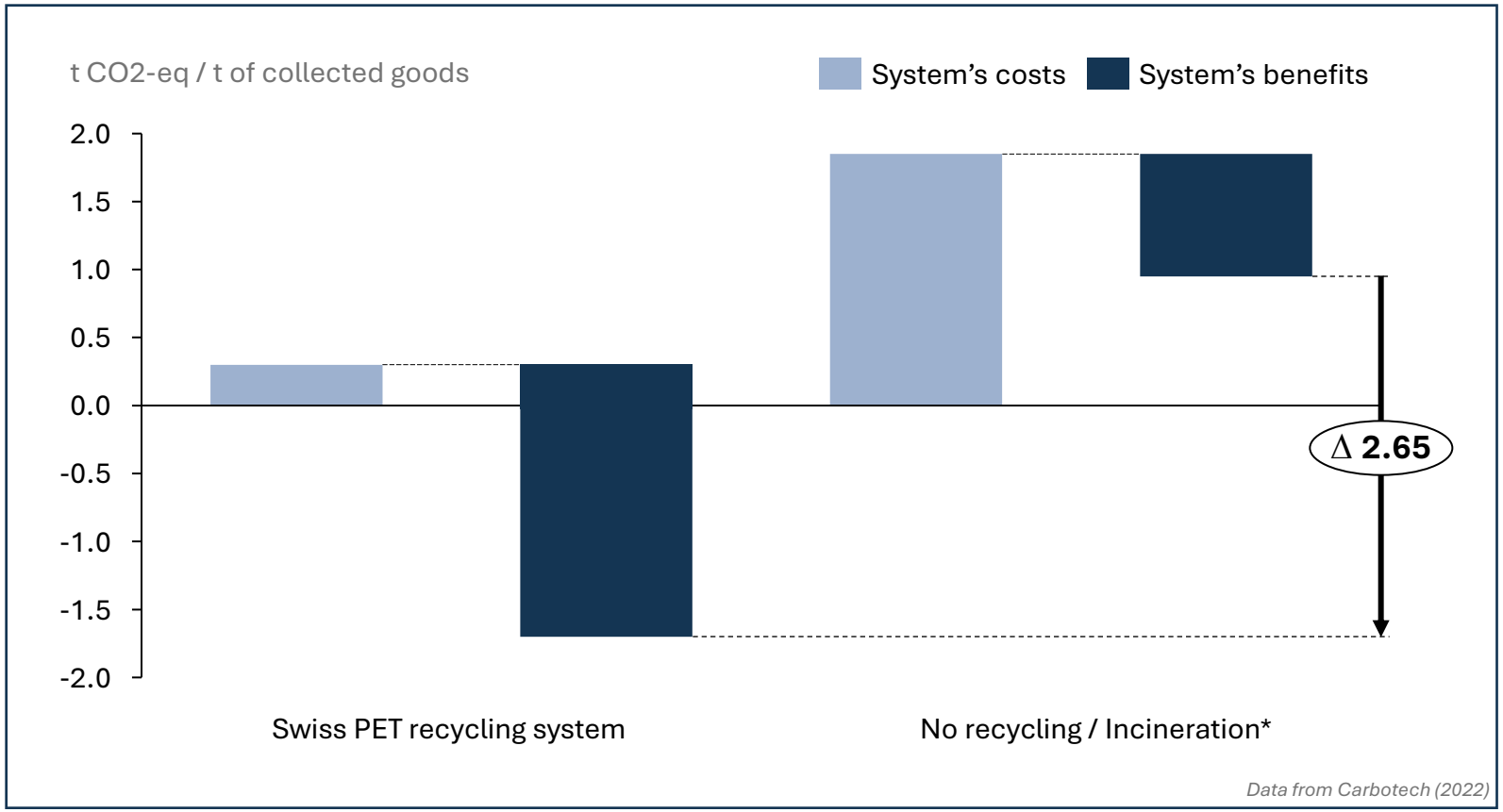


COLLECTION	TRANSPORT AND LOGISTICS	SORTING	RECYCLING	PRODUCTION AND BOTTLING
Bottles that are collected at more than 70,000 designated PET collection points are recycled	Compressing the bottles before returning them frees up space, thus conserving transport resources	Non-PET beverage bottles and other materials are removed, and PET is sorted by color before recycling to ensure high-quality recycled PET	The PET beverage bottles are shredded into flakes and pellets and then processed into high-quality recycled PET material	The recycled PET preforms are sent to manufacturers for bottle production, then refilled and sold

Sources: 1. PRS (2024)

Status quo | **The Swiss PET recycling system saved 2.65 t of CO_2-eq per tonne of collected goods in 2020***

The CO_2–eq footprint of the PRS recycling system compared to a simulated ”no recycling” scenario in 2020**



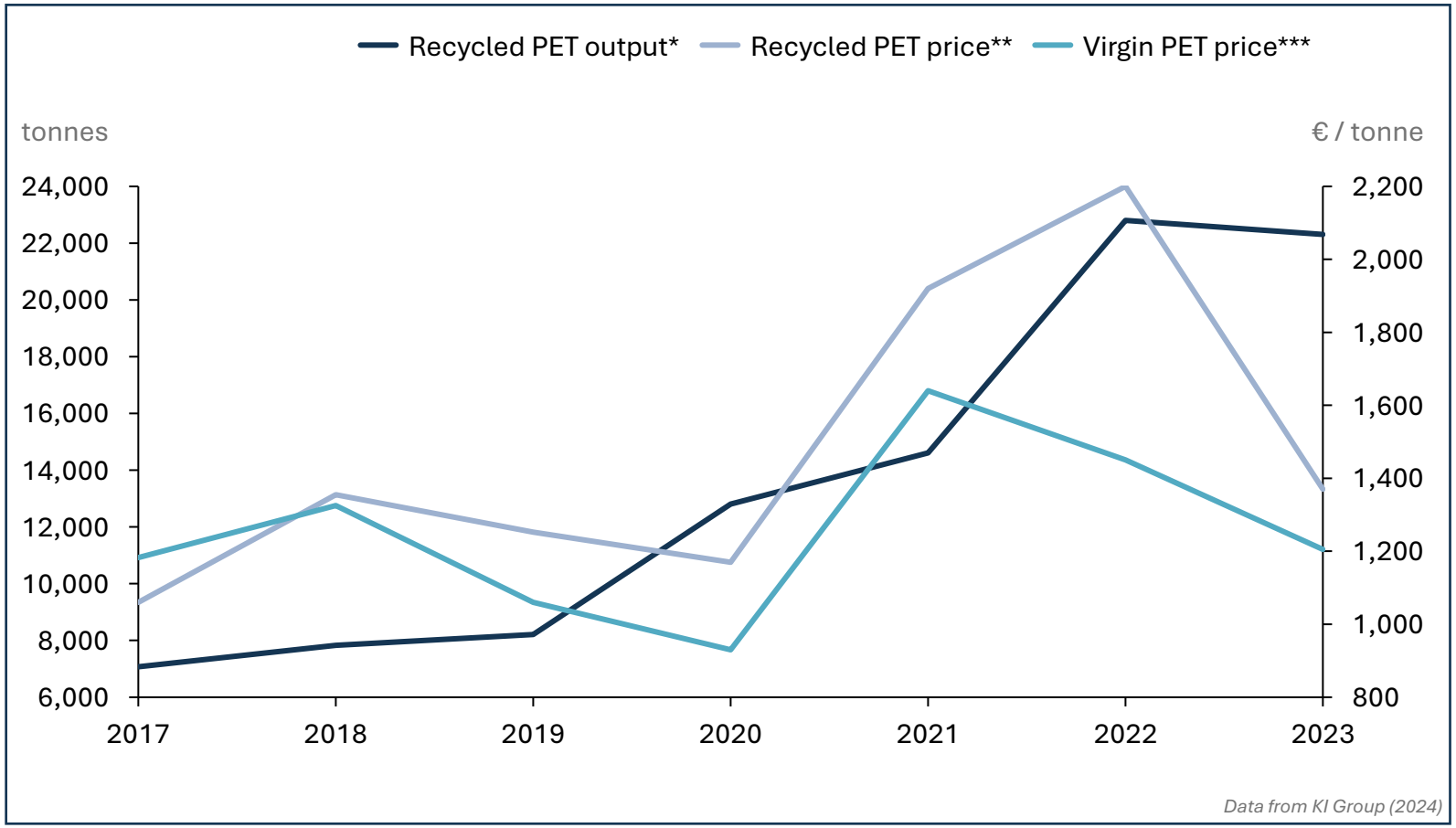
- Switzerland consumes more than 1.6 million PET bottles per year
- Each year, Swiss consumers bring over 80% of the PET beverage bottles (5 kg PET per citizen) to collection points[1]
- 2.65 t of CO2-eq per tonne of collected goods was saved through the PRS recycling system compared to no recycling in 2020[2]
- In the same year, the emission reduction amounted to 126,000 t, equivalent to ≈9,500 car trips around the world or heating ≈26,000 household for a year[2]

* Includes imports
** Municipal solid waste incineration (MSWI) where the MSWI generated electricity replaces European imported electricity and the generated heat replaces heat from crude oil (50%) and natural gas (50%)
Sources: 1. BAFU, 2023, 2. Carbotech (2022)

sus.lab

Status quo | **Recycled PET output experiences an upward trend, but prices remain volatile**

Swiss output of bottle-to-bottle recycled PET and recycled PET price in DACH market

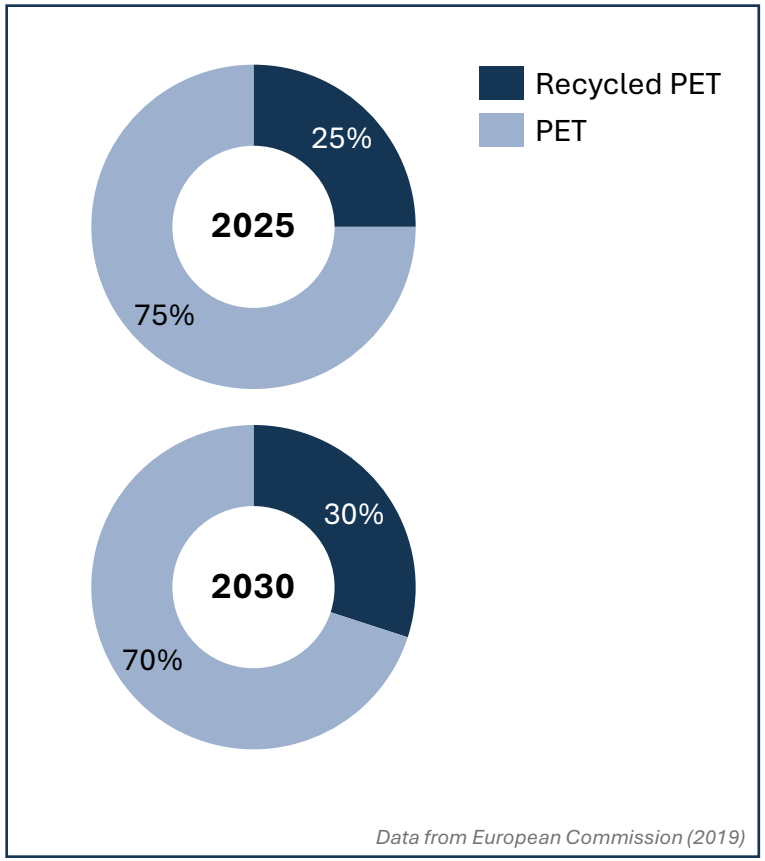


* Output of bottle-to-bottle recycled PET in Switzerland as of December 1st of a given year ** Price for clear, recycled PET in DACH region for December 1st of a given year *** Price for virgin PET for packaging in DACH region for December 1st of a given year **** Discrepancies in development of virgin and recycled PET prices in 2022 due energy crisis and limited supply of post-consumer PET bales
Sources: 1. Chemanaylst (2024)

- New regulations, as well as national and international brand commitments, continue to drive the demand for recycled PET
- The output of recycled PET for bottle-to-bottle has tripled since 2017
- A steep fall in prices for recycled PET in 2023 was caused by curbed demand for packaging with recycled materials[1]
- This was due to increased availability of post-consumer PET, negative demand forecasts for downstream industries, and favorable prices for virgin PET[1]
- The price of recycled PET reacts to changes in its output and virgin PET prices, making it volatile****

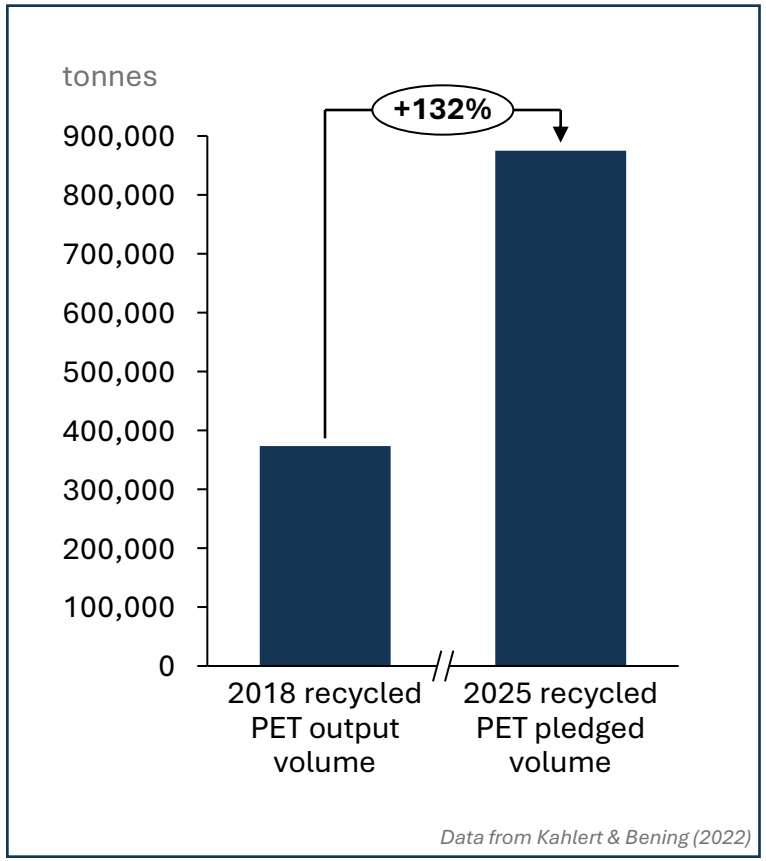
Status quo | **A significant increase in recycled PET is needed to meet the EU's targets and pledged volumes**

EU recycled PET content targets for plastic bottles by 2025 and 2030



Data from European Commission (2019)

EU recycled PET output for bottles in 2018 and pledged demand for 2025



Data from Kahlert & Bening (2022)

- As part of the Directive on single-use plastics, the EU has set targets to incorporate 25% of recycled PET in PET beverage bottles by 2025 and 30% by 2030[1]
- In addition to the mandatory targets, brand owners are making ambitious pledges regarding the recycled PET content in their PET bottles (more details on next page)
- The EU's recycled PET production volume, specifically for PET bottles, would need to increase by at least 132% from 2018 to 2025 to meet the brand owners' pledges[2]
- Given current technology, innovations, and scaling, it is unlikely that the pledged demand will be met by 2025[2]

Sources: 1. European Commission (2019); 2. Kahlert & Bening (2022)

Status quo | **Many brands are making ambitious pledges on the recycled PET content on the Swiss market**

Recycled PET content in PET bottles and brand pledges in Switzerland*

Company	Maximum recycled PET content in products	Recycled PET content in total portfolio	Brand pledges for recycled PET content in bottles
Company 1	100%	100%	Achieved 100% across product portfolio in 2021
Company 2	100%	100%	100% since May 2022
Company 3	100%	*No public information available*	*No public pledge for recycled PET*
Company 4	100%	*No public information available*	100% for water brands by 2025
Company 5	100%	55%	65% by 2030
Company 6	75%	75%	100% without due date
Company 7	100%	98%	*No public pledge for recycled PET*
Company 8	100%	60%	100% by 2025
Company 9	100%	*No public information available*	*No public pledge for recycled PET*
Company 10	100%	50%	Maximum available content of Swiss recycled PET in bottles

* An unexhaustive excerpt of publicly available certified, pledged, and average recycled PET content communicated by beverage companies in Switzerland
Sources: 1. PRS, 2023

- Most beverage companies in Switzerland already have products with 100% recycled PET content in their portfolios
- The average recycled PET content in beverage bottles in the Swiss market was 35% in 2019. By 2022, it had reached 60% (incl. imports), and it is expected to increase further by 2025[1]
- Brand pledges differ in scope, recycled PET content, and due dates among beverage companies, with some making no pledges regarding recycled PET content in beverage bottles

Table of content

Status quo of PET recycling in Switzerland and Europe		**05-09**
Limitations of 100% recycled PET in bottles	Limited supply	**11-20**
	Material degradation	
Prospects for PET recycling in Switzerland	Mechanical recycling	**22-30**
	Chemical recycling	
	Additives	

Limitations | **In the long run, implementing 100% recycled PET across the Swiss market is currently not feasible due to limited supply and material degradation**



LIMITED SUPPLY

Long-term 100% recycled PET use in beverage bottles across the Swiss market is currently not feasible due to:

1) **Losses during collection and in the sorting and recycling process**
2) **Demand from secondary markets***

Not all PET beverage bottles in circulation are collected for recycling and some material is lost during the recycling process. In addition, the demand for recycled PET from other markets other than PET beverage bottles could reduce the supply of PET available for bottle-to-bottle production.



MATERIAL DEGRADATION

Long-term use of 100% recycled PET in beverage bottles across the Swiss market is currently not feasible due to:

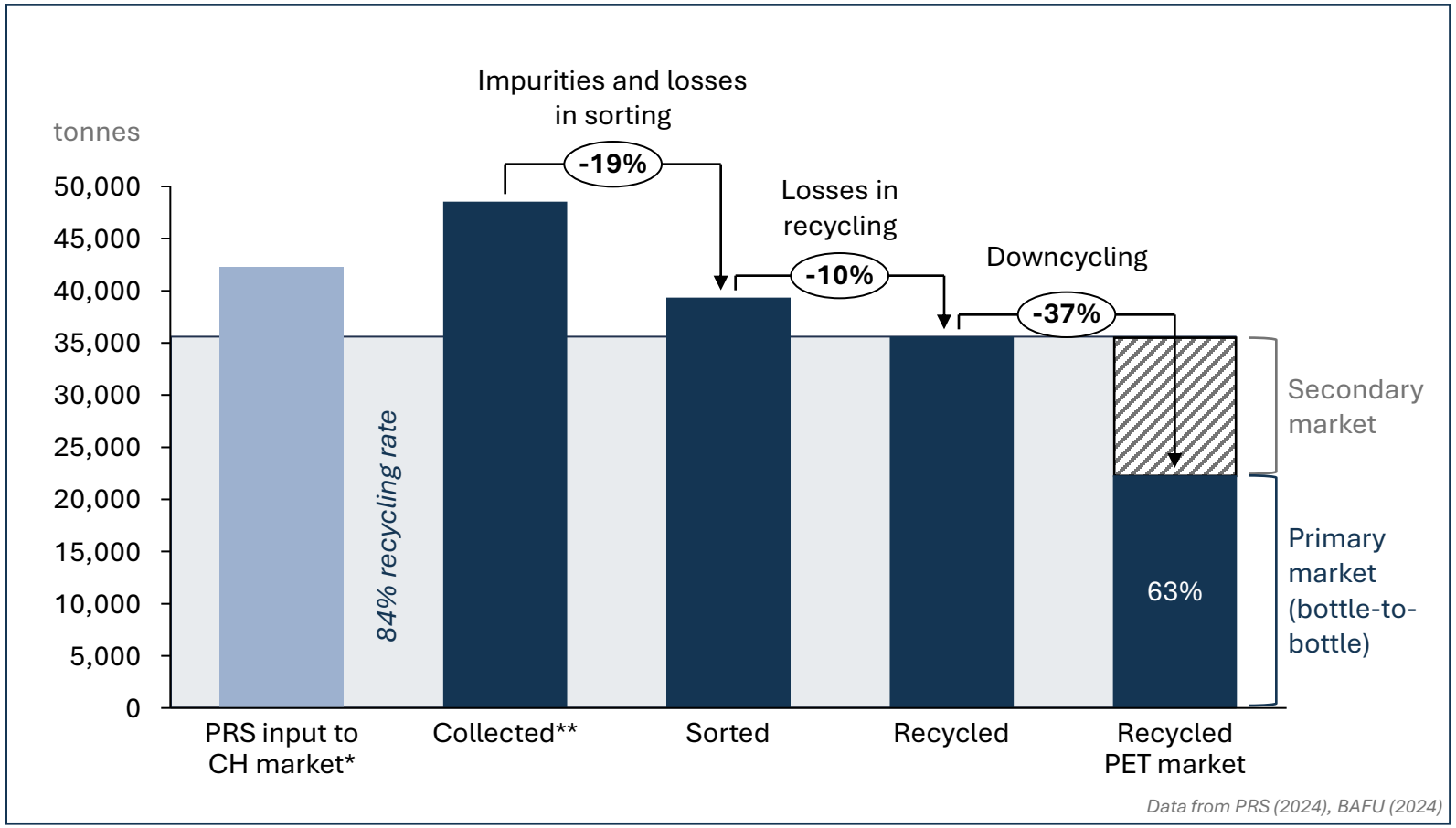
1) **Contaminant accumulation**
2) **Changes in optical properties****
3) **Changes in mechanical properties**

Contaminant accumulation, changes in optical properties, and changes in mechanical properties of PET tend to be negatively influenced by the increasing recycled PET content and the number of recycling cycles.

*In the Swiss context, beverage manufacturers have priority access to rPET; the remaining rPET is sold to secondary markets.
** So far, no concerns regarding optical changes have been raised by Swiss consumers.

Limitations | **The PET recycling process experiences significant material losses from collection to output**

The lifecycle of PET material from sales to output in 2023

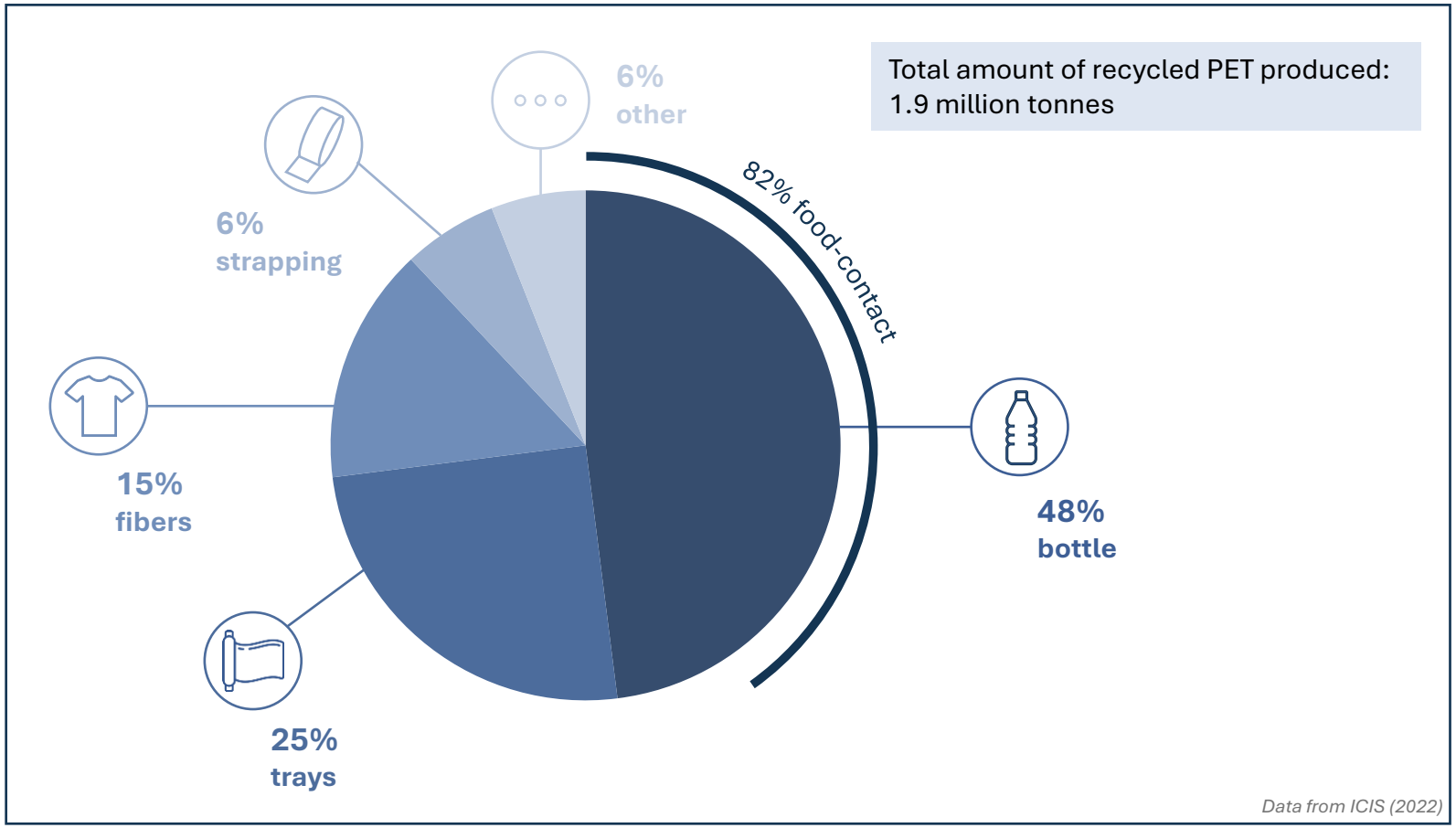


* Does not account for imports and exports
** Includes imports and impurities such as non-PET bottle, labels, caps, and leftover liquid
Sources: 1. BAFU (2024)

- Not all PET bottles in circulation are collected for recycling
- Losses of material occur both during the sorting step (e.g., sorting out impurities) and the mechanical recycling step (e.g., removal of contaminants, material degradation)
- In 2023, 84% of PET bottles in circulation were recycled[1] for primary (bottle-to-bottle) and secondary (e.g., strapping, fiber, films) markets
- Less than two-thirds of the recycled PET output is used within a closed-loop recycling system to produce new beverage bottles
- Material losses prevent the implementation of 100% recycled PET content in beverage bottles across the Swiss market

Limitations | **Less than half of the recycled PET output is used for bottle-to-bottle production in Europe**

The end markets for recycled PET in the EU27+3 region* in 2022



- In Switzerland, the bottle-to-bottle market is the largest market for recycled PET output[1]
- In Europe, the primary use for recycled PET is packaging, with 48% used in bottles (about 82% of which are for food contact) and 25% in trays through sheet extrusion[2]
- 27% is used for non-packaging applications such as fibers for cloths and strapping[2]

* EU member countries, Norway, Switzerland, and the United Kingdom
Sources: 1. PRS (2023), 2. ICIS (2022), 3. EU (2019)

Limitations | **PET cannot be recycled infinitely due to material degradation with each recycling cycle**



LIMITED SUPPLY

Long-term use of 100% recycled PET in beverage bottles across the Swiss market is currently not feasible due to:

1) Losses during collection and in the sorting and recycling process

2) Demand from secondary markets*

Not all PET beverage bottles in circulation are collected for recycling and some material is lost during the recycling process. In addition, the demand for recycled PET from other markets other than PET beverage bottles could reduce the supply of PET available for bottle-to-bottle production.



MATERIAL DEGRADATION

Long-term use of 100% recycled PET in beverage bottles across the Swiss market is currently not feasible due to:

1) **Contaminant accumulation**

2) **Changes in optical properties****

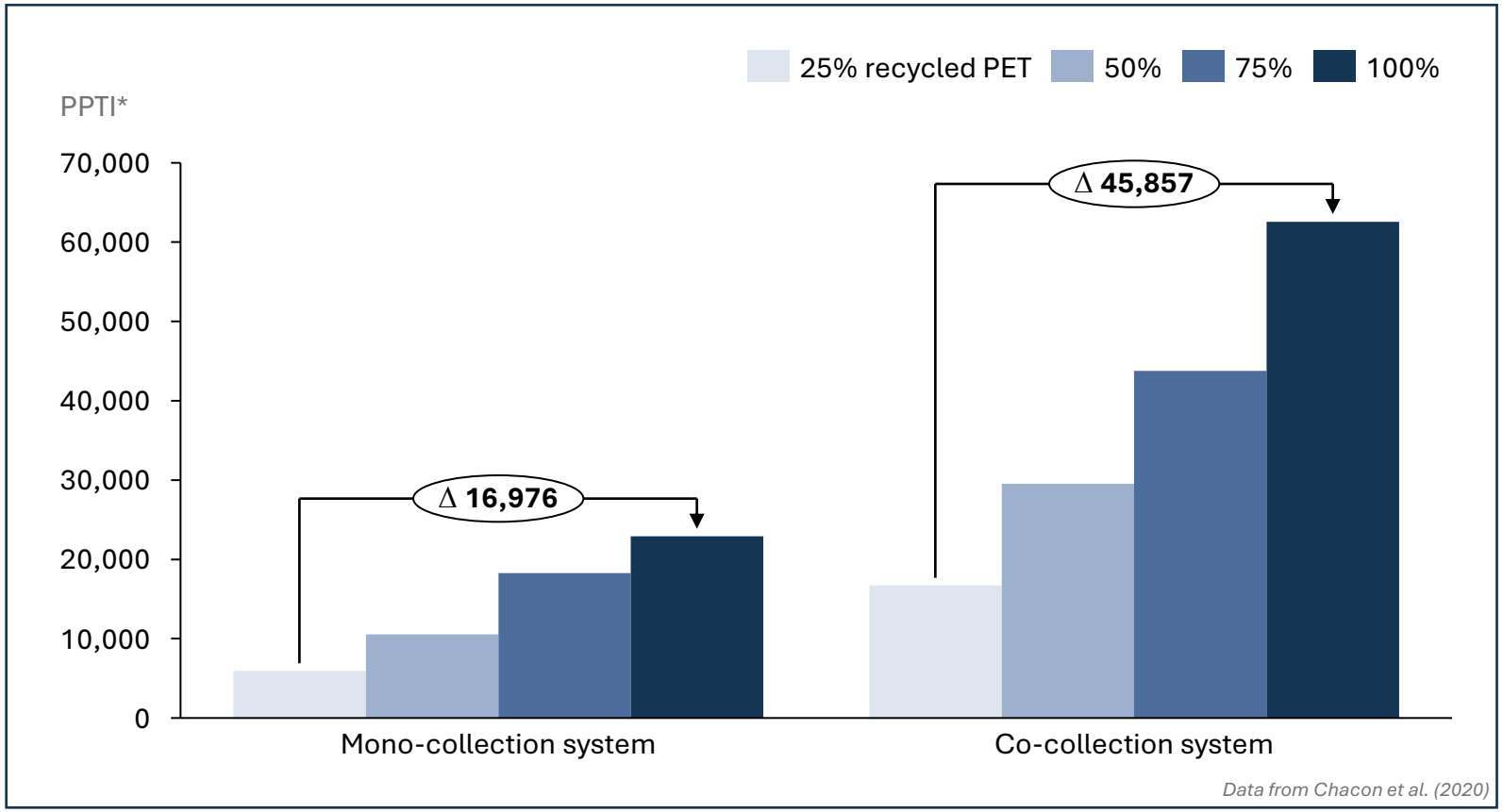
3) **Changes in mechanical properties**

Contaminant accumulation, changes in optical properties, and changes in mechanical properties of PET tend to be negatively influenced by the increasing recycled PET content and the number of recycling cycles.

*In the Swiss context, beverage manufacturers have priority access to rPET; the remaining rPET is sold to secondary markets.
** So far, no concerns regarding optical changes have been raised by Swiss consumers.

Limitations | **Particle contamination in bottles increases with raising recycled PET content**

Total particle count in bottles with different recycled PET contents from mono- and co-collection recycling schemes

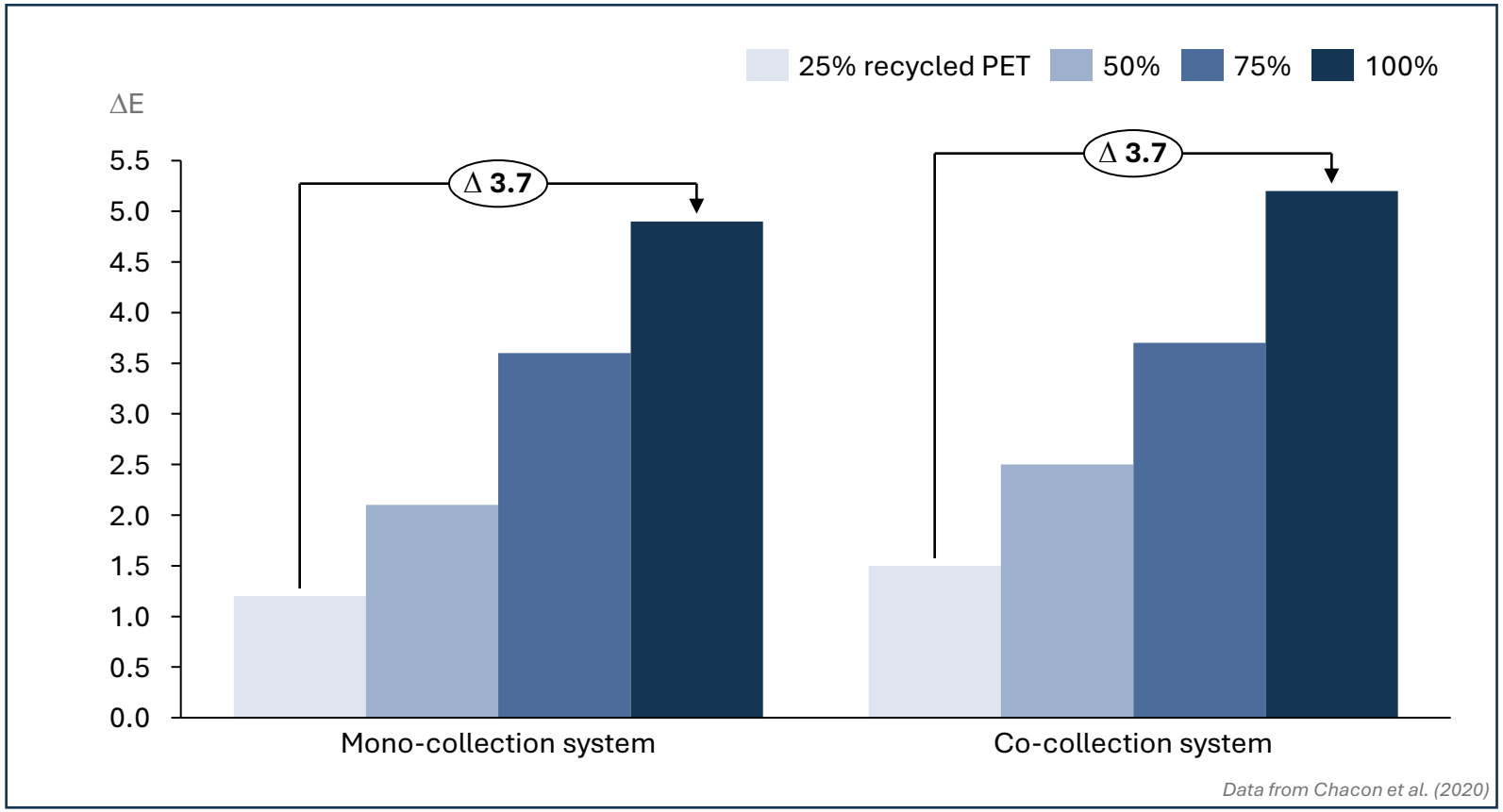


* PPTI = particles per 10,000 images
** Includes high temperature wash, gas wash, and chemical wash
Sources: 1. Chacon et al. (2020); 2. Brouwer et al. (2020); 3. Benyathiar et al. (2022); 4. Franz et al. (2003); 5. Pinter et al. (2021)

- Particle contamination occurs across all steps of the bottle's lifetime (e.g., usage, collection, and recycling) and also in virgin PET bottles (1,525 PTTI)[1,2]
- Particle contamination increases with recycled PET content and tends to be higher in co-collection recycling systems[1,2]
- More than 70% of the detected particles measure from 0 to 3 µm, and 90% of the particles are smaller than 5 µm[1]
- Contamination in beverage bottles can be reduced via super-clean recycling processes (i.e., deep-clean recycling)**[3,4,5]

Limitations | **Changes in color of beverage bottles increases with recycled PET content**

Total color difference between bottles with recycled PET content and virgin PET bottles (ΔE*) from mono- and co-collection recycling schemes



Data from Chacon et al. (2020)

* $\Delta E = [(\Delta L^{*2})+(\Delta a^{*2})+(\Delta b^{*2})]^{1/2}$ where L* (100 = white, 0 = black) indicates greying, a* (positive = red, negative = green, 0 = grey), and b* (positive = yellow, negative = blue, 0 = grey) indicates yellowing

Sources: 1. Chacon et al. (2020); 2. Benyathiar et al. (2022)

- L* (lightness) is unrelated to the collection system and decreases with recycled PET content[1]
- b* (yellowness) depends on the collection system and increases with recycled PET content only under the co-collection condition[1]
- Haze (light diffusion) increases with recycled PET content and is linearly correlated with particle contamination ($R^2 = 0.96$)[1]

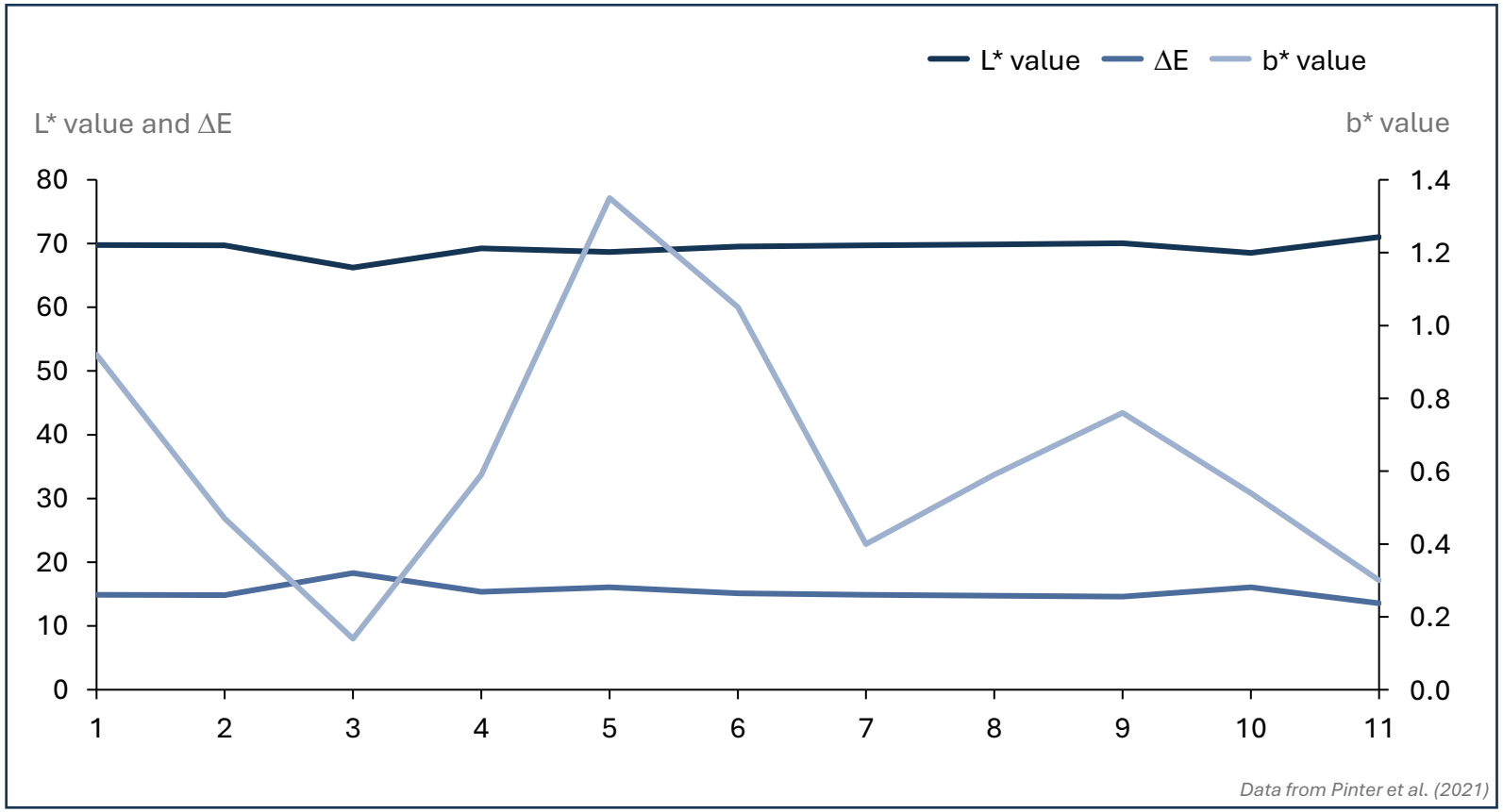


0% Recycled PET | 25% | 50% | 100% | 100% Recycled PET + toner

Taken from Benyathiar et al. (2022)

Limitations | **High-quality material and additives can be used to combat the unwanted color change**

The total color change (ΔE) and color parameters (L* and b*) for a beverage bottle with 75% recycled PET and 25% virgin PET content over 11 recycling cycles



Data from Pinter et al. (2021)

* $\Delta E = [(\Delta L^{*2})+(\Delta a^{*2})+(\Delta b^{*2})]^{1/2}$ where L* (100 = white, 0 = black) indicates greying, a* (positive = red, negative = green, 0 = grey), and b* (positive = yellow, negative = blue, 0 = grey) indicates yellowing

Sources: 1. Pinter at al. (2021)

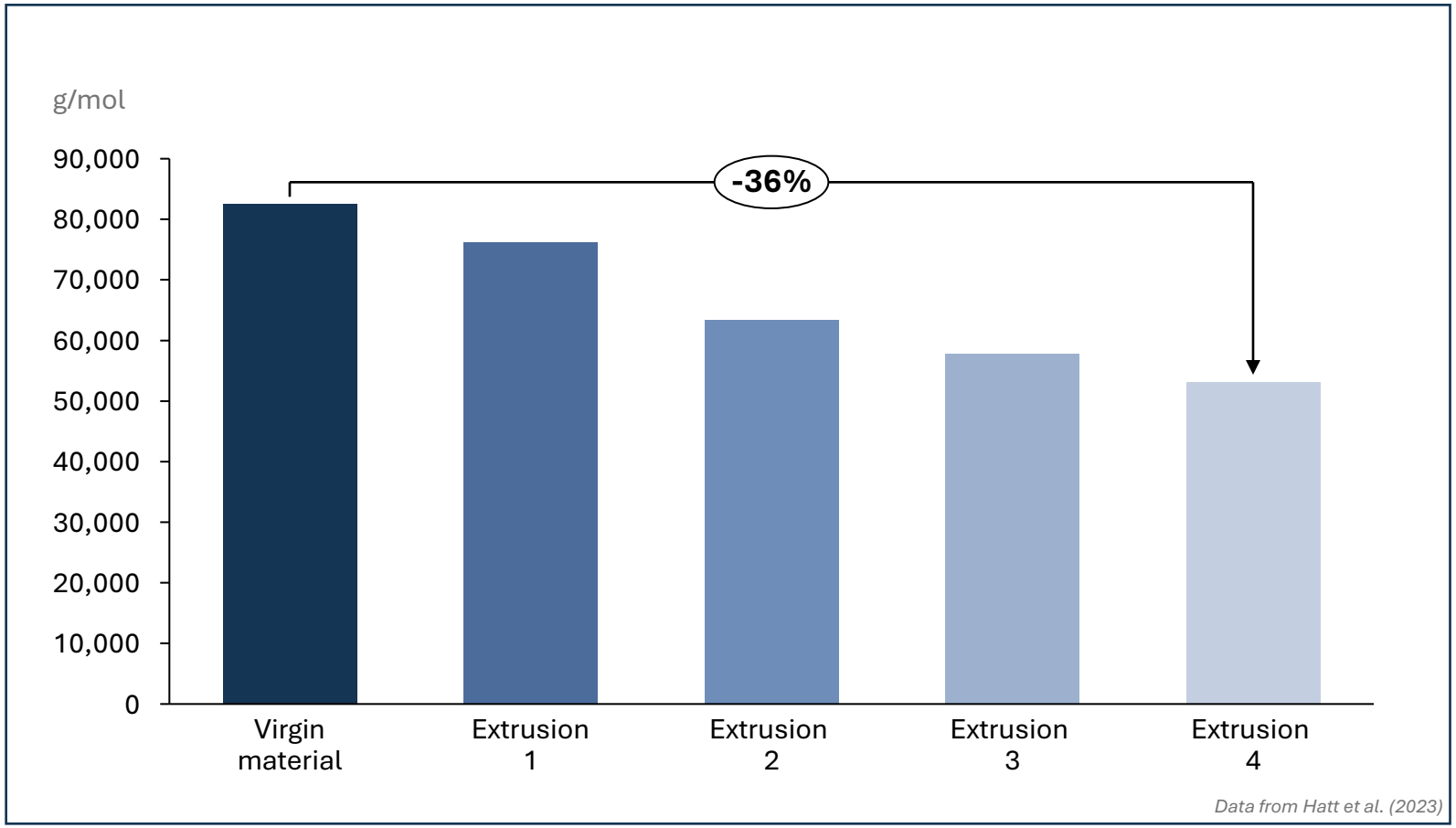
- Color change is a known problem in mechanical recycling and needs to be closely monitored
- Good-quality material with low levels of contamination can prevent the unwanted color change
- In an experiment with a 75% recycled PET content bottle, hazing/greying was not an issue. Additives were used to combat the unwanted yellowing (increase in b* above 2.0), which kept b* values at desired levels over all cycles[1]



Adapted from Pinter et al. (2021)

Limitations | **Repeated mechanical recycling decreases the molecular weight of PET**

Weight-average molecular weight of virgin PET material before and after 4 extrusion cycles

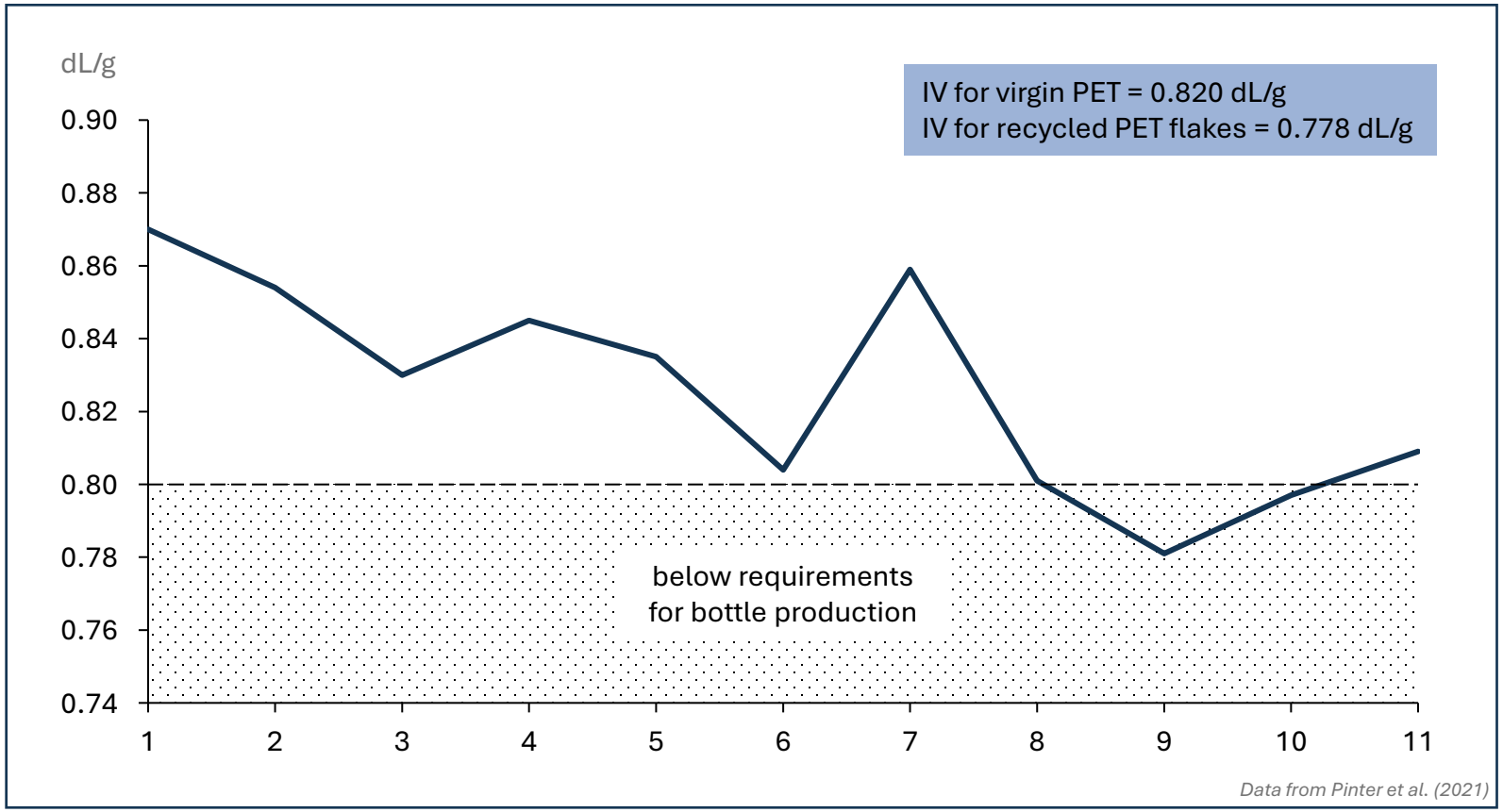


- PET recycling includes an extrusion step, during which PET undergoes melt processing using high heat
- The repeated heating experienced during each recycling cycle* has the potential to significantly affect physical, thermal, rheological, mechanical, and morphological properties of PET, including the reduction in molecular weight[1]
- The reduction in molecular weight due to thermomechanical degradation of polymer chains can result in a significant drop in intrinsic viscosity (IV)[2]
- Lower IV values can indicate reduced tensile strength, toughness, and impact resistance of the beverage bottle[2]

* Due to processing steps such as extrusion or molding
Sources: 1. Hatt et al. (2023); 2. Chacon et al. (2020)

Limitations | **Solid-state polycondensation manipulation can be used to limit the decrease in intrinsic viscosity**

IV for a beverage bottle with 75% recycled PET and 25% virgin PET content over 11 recycling cycles



* Bottle grade IV value = 0.70 – 0.78 dL/g[2], Water and soft drink bottle grade = 0.78 – 0.85 dL/g[3]
** Process in which polymerization mainly takes place in the amorphous regions of the polymer, leading to increased crystallinity in the final product
Sources: 1. Pinter et al., (2021); 2. Chairat & Gheewala (2023); 3. ICPG (2021)

- A high PET IV value is required to meet market requirements for beverage bottle production*[1,2,3]
- Solid-state polycondensation** (SSP) is the main process used in mechanical recycling to maintain or increase PET IV values
- By manipulating the parameters within the SSP process, the decrease in IV values due to repeated recycling has the potential to be prevented
- In an experiment with a 75% recycled PET content bottle, the decrease in IV below the requirement for bottle production (IV >0.8) after 9 cycles was compensated for through SSP parameters adjustment

Limitations | **Given today's technology, supply, and demand, the suggested threshold for recycled PET content in beverage bottles is 75-80%**

Limited supply and material degradation

Limited supply	• Given brands' pledges and governmental targets, the demand for recycled PET is expected to rise • The current recycled PET production volume is not enough to meet the expected increase in demand • Individual beverage bottles with 100% recycled PET content are possible but on a system level the suggested threshold for recycled PET content in beverage bottles is 75-80% • PET recycling does not work on a one-to-one basis, meaning that one recycled PET bottle will not result in one new recycled PET bottle due to material loss in recycling • There is demand for recycled PET from secondary markets (e.g., films, strapping), which could decrease the amount of recycled PET available for bottle-to-bottle production*
Material degradation	• 100% recycled PET in a closed loop system should only be attempted if all critical contaminants can be completely removed[1] • Given today's mechanical recycling process, completely removing all critical contaminants is currently not possible[1]. The addition of virgin PET to beverage bottles becomes necessary to meet the desired properties and quality standards • Over 11 recycling cycles, PET beverage bottles consisting of 25% virgin PET and 75% recycled PET experienced no significant material degradation**, indicating the potential for continuous recycling without sacrificing quality[2] • PET bottles within recycling schemes using mono-collection systems can contain more recycled content (due to the lower levels of contamination) than those from co-collection systems[2]
Industry example	• In 2021, IMSDAL (a non-carbonated Norwegian water brand) reduced the recycled PET content in their beverage bottles from 100% to 80% with the goal of extending the life of the material and ensuring repeated recycling with adequate quality[3]

* In the Swiss context, recycled PET has been exclusively supplied for PET bottle production thus far.
** Additives were used and adjustment to the recycling process were made to achieve this result.
Sources: 1. Brouwer et al. (2020); 2. Pinter et al., (2021); 3. Pindsle & Cundari 2023

Table of content

Status quo of PET recycling in Switzerland and Europe		**05-09**
Limitations of 100% recycled PET in bottles	Limited supply	**11-20**
	Material degradation	
Prospects for PET recycling in Switzerland	Mechanical recycling	**22-30**
	Chemical recycling	
	Additives	

Prospects | **A range of strategies exists to continuously improve PET recycling techniques and increase the recycled PET content in beverage bottles**

MECHANICAL RECYCLING

Mechanical recycling is a **widely used** technology with lower environmental impacts than virgin PET production and chemical recycling.

However, the technology has its **limits**, as it is not effective **in** removing impurities and contaminants that accumulate.

These impurities and contaminants cause **material degradation** during the continuous recycling of the material.

CHEMICAL RECYCLING

Chemical recycling can **restore PET properties** to virgin-like grade by removing impurities.

The technology has lower **environmental impacts** than virgin PET production; however, its impacts are higher than those of mechanical recycling.

The application of chemical recycling is currently **limited** by the high cost and early-stage development of the process.

ADDITIVES

Additives in PET production can be used to **alter the properties** of the polymer.

Additives can be added to **limit and/or reverse** PET degradation and allow for an increase of recycled PET content in beverage bottles.

The **effects of additives** in recycled PET production over multiple cycles, including health risks and safety concerns, are not yet fully understood and continue to be studied.

Prospects | **Further developments in mechanical recycling are needed to minimize PET degradation and promote the reusability of PET**

Drivers and barriers of mechanical PET recycling

Widely used technique	• Mechanical recycling is the most widely used PET bottle recycling technique[1] • The aim of alternative/advanced recycling methods (e.g., chemical recycling) is not to replace mechanical recycling but rather to tackle inputs unsuitable for mechanical recycling (e.g., plastics from mixed waste or highly contaminated plastics)[2]
Environmentally friendly	• Mechanical recycling has the potential to reduce greenhouse gas (GHG) emissions and conserve natural resources[3] • According to life-cycle assessment (LCA) studies, mechanical recycling has lower emissions than chemical recycling and conventional PET production[4, 5]
Not effective at removing impurities and contaminants	• PET contamination occurs both during the product's lifetime and during the recycling process[6] • The addition of additives can contribute to the accumulation of contaminants and impurities[7] • Contaminant and impurity accumulation can also contribute to color change, which can impact the bottle's appeal to the customer, especially in the case of clear liquids such as water[7, 8]
Causes material degradation	• Repeated heating during mechanical recycling cycles has the potential to cause degradation of PET material[7, 9] • Continuous degradation (including contaminant accumulation) is likely to eventually lead to a low-quality PET, which cannot be used in food-contact plastics such as beverage bottles[2]

Sources: 1. Plastics Europe (2024a); 2. Plastics Europe (2024b); 3. Joseph et al. (2024); 4. Systemiq (2023); 5. Joseph et al. (2024); 6. Brouwer et al. (2020); 7. Chacon et al. (2020); 8. HCA (2022) ; 9. Brouwer et al. (2020)

Prospects | **A range of strategies exists to continuously improve PET recycling techniques and increase the recycled PET content in beverage bottles**



MECHANICAL RECYCLING

Mechanical recycling is a **widely used** recycling technology with lower environmental impacts than virgin PET production and chemical recycling.

The technology has its **limits** with not effectively removing impurities and contaminants that are accumulating.

These impurities and contaminations cause **material degradation** during continuous recycling of the material.



CHEMICAL RECYCLING

Chemical recycling can **restore PET properties** to virgin-like grade by removing impurities.

The technology has lower **environmental impacts** than virgin PET production; however, its impacts are higher than those of mechanical recycling.

The application of chemical recycling is currently **limited** by the high cost and early-stage development of the process.



ADDITIVES

Additives in PET production can be used to **alter the properties** of the polymer.

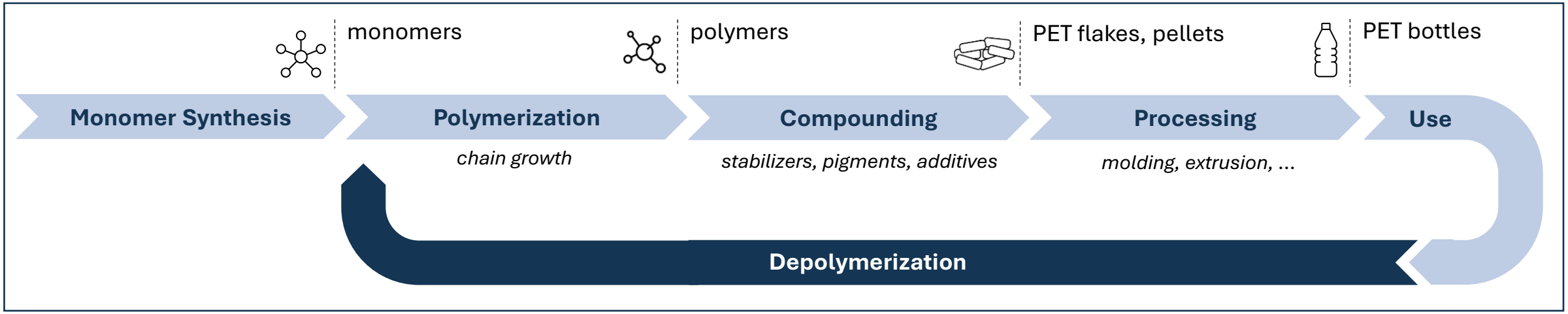
Additives can be added to **limit and/or reverse** PET degradation and allow for an increase of recycled PET content in beverage bottles.

The **effects of additives** in recycled PET production over multiple cycles, including health risks and safety concerns, are not yet fully understood and continue to be studied.

Prospects | **Chemical recycling can depolymerize PET polymers into their monomers and potentially restore the material's virgin-like properties**

Chemical recycling* technologies

Depolymerization**	Depolymerization is a process in which a polymer is broken down into virgin-like monomers (or oligomers) through a reaction with chemical agents[1,2,3]	
	Glycolysis	• Polyester renewal technology using ethylene glycol to break down PET[1]
	Hydrolysis	• Polyester renewal technology using water to break down PET
	Methanolysis	• Polyester renewal technology using methanol to break down PET (the most common form of alcoholysis)



* Chemical recycling consists of depolymerization and thermal conversion, the latter is excluded from the scope of this report
** Also referred to as solvolysis or chemolysis by some authors[3]
Sources: 1. Benyathiar et al. (2022); 2. Ragaert et al. (2017); 3. FOEN (2023)

Prospects | **Chemical recycling offers the potential to restore PET's virgin-like properties but requires investments to be commercially viable (I/II)**

Drivers and barriers of chemical PET recycling

Restores virgin-like properties*	• Depolymerizing PET into its monomers limits material degradation (e.g., thermal-mechanical) that would otherwise occur with mechanical recycling[1,2] • Breaking down PET into its monomers offers a higher degree of flexibility for future use[1]
Removes impurities	• Contrary to today's mechanical recycling technology, chemical recycling can remove contaminants (e.g., additives, heavy impurities, or colorants) to upcycle non-food grade PET to food-grade PET[3,4] • Chemical recycling (e.g., via alkaline hydrolysis) is likely to be more effective in removing contaminants and impurities[1,5,6] • Chemical recycling is resistant to the low purity and quality of certain waste PET sources, especially in the case of colored PET bottles[3]
Environmental impacts	• LCA studies indicate that chemical recycling has lower GHG emissions than virgin PET manufacturing and higher GHG emissions than mechanical recycling[7] • Compared to virgin PET production, chemical recycling can reduce GHG emissions and energy consumption by up to 50%[1] • To reduce the environmental footprint of chemical recycling, investing in the use of renewable feedstock (e.g., biomass) to produce monomers can be beneficial[1]

* The extend to which this is possible needs further research
Sources: 1. Joseph et al. (2024); 2. Ragaert et al. (2017); 3. McNeeley & Liu (2024); 4. Brouwer et al. (2020); 5. Babaei et al. (2024); 6. Ügdüler et al. (2020); 5. 7. Systemiq (2023)

Prospects | **Chemical recycling offers the potential to restore PET's virgin-like properties but requires investments to be commercially viable (II/II)**

Drivers and barriers of chemical PET recycling

Expensive process	• Chemical recycling often targets “hard-to-recycle” waste, requiring specialized equipment and expertise, which can lead to high costs due to factors such as raw material costs, capital investment, and scale of operations[1,2,3] • The average annual operating costs (OPEX) of depolymerization are estimated to be $1,195 per tonne, and the average capital costs (CAPEX) are estimated to be $1,300 to $1,900 per tonne*[4]
Not economically and commercially viable	• While chemical depolymerization has the potential to produce high-purity outputs, high yields appear to be possible only with clean and homogeneous inputs[5] • As the demand for recycled PET continues to rise, it will become increasingly important to develop more efficient and cost-effective chemical recycling processes[1]
New process with many unknowns	• There is insufficient information regarding the nature, quantity, and toxicity of the solvents and chemicals used, as well as a potential lack of clarity in legislation[6] • What happens to the waste and by-products generated during the chemical recycling process remains, in some cases, unclear[6]

* Data based on datasets provided by early commercial and pilot technologies companies; throughput capacity of 29,500 tonnes per year
** The specific minimum number required can differ based on technology used
Sources: 1. Joseph et al. (2024); 2. Plastics Europe (2024); 3. George & Kurian (2014); 4. CLP (2021); 5. Tabrizi (2021); 6. Hann & Connock (2020)

Prospects | **A range of strategies exists to continuously improve PET recycling techniques and increase the recycled PET content in beverage bottles**



MECHANICAL RECYCLING

Mechanical recycling is a **widely used** recycling technology with lower environmental impacts than virgin PET production and chemical recycling.

The technology has its **limits** with not effectively removing impurities and contaminants that are accumulating.

These impurities and contaminations cause **material degradation** during continuous recycling of the material.



CHEMICAL RECYCLING

Chemical recycling can **restore PET properties** to virgin-like grade by removing impurities.

The technology has lower **environmental impacts** than virgin PET production; however, its impacts are higher than those of mechanical recycling.

The application of chemical recycling is currently **limited** by the high cost and early-stage development of the process.



ADDITIVES

Additives in PET production can be used to **alter the properties** of the polymer.

Additives can be added to **limit and/or reverse** PET degradation and allow for an increase of recycled PET content in beverage bottles.

The **effects of additives** in recycled PET production over multiple cycles, including health risks and safety concerns, are not yet fully understood and continue to be studied.

Prospects | **Additives enable increased recycled PET content in beverage bottles, but their effects over many cycles are not yet fully understood (I/II)**

Additive group*	Explanation	Common examples
Colorants	• Colorants are used to improve the color (i.e., yellowing) and haziness of PET bottles[1] • Colorants are particularly important in bottles meant for clear beverages, where greying/haziness can affect the product's attractiveness to customers[2]	• Blue colorants and toners • Inorganic pigments – e.g., Titanium dioxide (TiO2)**[3]
UV absorbers and stabilizers	• UV absorbers and stabilizers are used to protect PET bottles from degradation due to environmental exposure, such as ultraviolet (UV) radiation	• UV 326, 327, 328, 329[5] • Tinuvin 1577[6,8] and 234[6]
Catalysts	• Catalysts are used to accelerate the chemical reaction during the polymerization process of PET production • They increase the efficiency of the reaction, save energy, and reduce costs	• Antimony (Sb) – e.g., antimony trioxide (Sb_2O_3)[8,9]
Reheat additives	• Reheat additives are used to improve the thermal properties of PET and promote more efficient and uniform heating of the material[10] • PET material can often vary in reheat additive concentration, as it is not widely used in all countries[11]	• Carbon black[10,12]
Acetaldehyde scavengers	• Acetaldehyde is one of the undesired by-products/pollutants generated during PET degradation due to factors such as sunlight or high temperature exposure[13,14] • Acetaldehyde scavengers are used to reduce the concentration of acetaldehyde in PET and, consequently, the migration of acetaldehyde into the bottle's contents[15] • Particularly important in PET bottles meant for mineral water as migrated acetaldehyde can negatively impact taste, leading to an "off-taste"[16,17]	• Anthranilamide[16] • 2-Aminobenzamide[17]

* Not an exhaustive list; categorization of additive groups can differ between sources
** banned in EU since 2022[2]

Sources: 1. Chacon et al. (2020); 2. HCA (2022); 3.Turner & Filella (2023); 4. EC (2022); 5. Rani et al. (2017); 6. Begley at al. (2007); 7. Fechine et al. (2004); 8. Duh (2002); 9. Filella (2020); 10. Harrison & Davis (2005); 11. Benyathiar et al. (2022); 12. van Velzen et al. (2020); 13. Depaolini et al. (2020); 14. Villain at el. (1995); 15. Gehring & Welle (2017); 16. Bach et al. (2012); 17. Franz et al. (2015)

Prospects | **Additives enable increased recycled PET content in beverage bottles, but their effects over many cycles are not yet fully understood (II/II)**

Additive group*	Explanation	Common examples
Compatibilizers	• Compatibilizers are used when blending recycled PET with PET or other polymers to promote homogeneity in the polymer blend and enhance the desired mechanical properties[1,2,3]	• Polypropylene-graft-maleic anhydride (PP-g-MAH)[4,5,6] • Styrene-ethylene/butylene-styrene-maleic anhydride-graft (SEBS-g-MAH)[4,5,6]
Antioxidants	• Antioxidants are used to prevent or delay PET oxidation (i.e., oxidative degradation)[7]	• Phenolics (e.g., Irganox 1010)[7] • Organophosphites (e.g., Irgafos 168)[7]
Chain extenders	• Chain extenders are used to repair and extend polymer chains that might have degraded due to thermomechanical and hydrolytic degradation during mechanical recycling[8]	• Pyromellitic dianhydride (PMDA)[8]
Non-intentionally added substances (NIAS)	• NIAS can result from impurities (e.g., residual contaminants), reaction products during PET production, and/or polymer and additive degradation[9] • Additives can be used to remove some of the known NIAS (e.g., acetaldehyde via acetaldehyde scavengers)[9] • The addition of additives can also lead to the production of NIAS (e.g., alkylphenols from antioxidants)[10] • Studies have found higher contamination in recycled PET, which mandates close monitoring to address safety and health concerns[9]	• Acetaldehyde[9] • Benzene[9] • Alkylphenols[10]

* Not an exhaustive list; categorization of additive groups can differ between sources

Sources: 1. Baird (2003); 2. Musa et al. (2022); 3. Nofar (2021); 4. Mengual et al. (2017); 5. Papadopoulou & Kalfoglou (2000); 6. Razak et al. (2013); 7. Hahladakis et al. (2018); 8. Rashwan et al. (2023); 9. Gerassimidou et al. (2022); 10. Wagner et al. (2024)

CONTACT

Sophie Führer – Project Manager @ sus.lab
Gabriela Vojtova – Research Assistant @ sus.lab
Julia Bachmann – Co-Lead @ sus.lab
Prof. Catharina Bening – Head Circular Economy research @ SusTec

sus.lab is the Sustainability in Business Lab, an initiative of
SusTec, the Sustainability and Technology Chair at ETH Zürich
www.suslab.ch

sus.lab
Sustainability in Business Lab | ETH zürich