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Executive Summary

While plastic packaging and other plastic products have great benefits to civilization, the current and historical approaches to end-of-life management have resulted in significant challenges, particularly in recovering and retaining the economic and technical value of the materials and preventing plastic pollution. Most plastics put on the market end up in landfills or the natural environment, representing a significant environmental and societal impact as well as a loss of economic value [1]. The current plastics recycling rate in the United States (U.S.) hovers around 9 %, while approximately 70 % of recyclable polyethylene terephthalate (PET) and high-density polyethylene (HDPE) packages are lost to landfills and the environment [2, 3].

As the environmental and human health impacts of plastic waste become better understood, many brands have committed to ambitious recycled content targets, aiming to support a circular economy and reduce plastic waste. Several U.S. states have also proposed or implemented recycled content mandates (e.g., [4], [5], [6], and [7]). The dominant route for recycling recovered plastic has been mechanical recycling. Indeed, there is increasing demand for quality feedstocks for mechanical recycling and opportunities to expand this route, which is less resource intensive than many alternatives. However, existing mechanical recycling infrastructure is limited in its ability to recover all types of plastic waste, as well as to supply the quality and quantity of recycled material needed to meet some brand goals, functional requirements, and mandates in the range of sectors where mandates are expected, such as food packaging, medical-grade applications, and transparent materials (e.g., automotive headlamp lenses). As a result, chemical recycling — the reduction of polymers to their original monomer form or other small molecule precursors for reintroduction to the supply chain — has great appeal, especially for the polymeric products which still pose a challenge for mechanical recycling methods. Due to the nature of chemical recycling, specifically that chemically recycled carbon atoms and organic molecules become identical to virgin feedstocks and thus not traceable or measurable in the process, Mass Balance (MB) accounting is a tool that has been proposed, and is already being applied in some cases, to track, trace, and certify circular polymers. While MB certification standards have an extensive history in other commodity sectors, they have only recently been considered in the polymers sector in part due to recent technology advances and incentives to expand the scale of chemical recycling.

If properly supported and expanded, by 2050, nearly 60 % of plastics production could be sourced from complementary mechanical and chemical recycling routes globally [8] and the new materials could generate $2 billion to $4 billion of earnings annually. [9] The only way to transform the system and reach these goals is through rapid and diversified expansion of a range of technologies. Use of such technologies raises several questions and concerns, however, including:

- the ability of collection and sortation infrastructure to supply the necessary feedstock quantities and quality,
- the trade-offs in energy consumption and overall environmental impacts between the various routes,
- scalability of the various technologies,
- market size and especially competition with alternative materials and pathways,
- the attributes of the range of resulting products, such as fuels, and the energy demands of some chemical processes, and
- the quality and available quantities of qualifying recovered feedstock streams (e.g., material supply) – the single biggest limiting factor in BOTH pathways to more circular polymers.

The Save Our Seas 2.0 Act (SOS 2.0) (Public Law 116-224), which passed in December 2020, tasked the National Institute of Standards and Technology (NIST) with performing a study on MB methodologies to certify circular polymers. In this effort, NIST held a three-day workshop entitled “Assessment of Mass Balance Accounting Methods for Polymers” in May 2021. The purpose of the workshop was to convene stakeholders with interest in MB methodologies for circular polymers, including existing standardization and certification programs focused on polymer products as well as relevant expertise from other, comparable industries. The workshop included three plenary presentations and six topic-specific sessions with knowledgeable speakers and breakout roundtable discussions. Key findings from the workshop include:

1. MB accounting is a key enabler to accelerating adoption of chemical recycling technology, which will increase the amount of both circular polymers and recycled content in the supply chain.
2. MB accounting is not a new concept, but it is only newly being applied to the manufacture of polymers from recovered polymer feedstocks.
3. There are many unsettled issues, ill-defined terms, and conflicting objectives with regards to the application of MB certification to polymers.
4. Clear goals and objectives are necessary to align supply chain partners and certification components accordingly and ensure a reliable structure, support, and buy-in from stakeholders.
5. Using common, well-defined approaches to set boundary conditions (geographical and temporal) is critical to determine the applicability of the MB system and establish its scope.
6. Interoperability of tools and data frameworks across standards and certification systems is important for integrity and transparency and requires aligning certain definitions, terminology, and methods.
7. Legal and regulatory barriers include:
    a. The variability of regulations at state and local levels, which often mandate recycled content, but may exclude or prohibit chemical recycling, and may set conflicting standards for MB certification.
    b. Complying with local regulations versus national or global agreements, which could result in conflicting requirements, and suboptimal system-level decision making.
8. Alignment around key components of an MB framework is necessary for credibility.
9. There are significant and complex needs related to education, research, and development:
    a. Clear and consistent messaging (business-to-business and to the consumer) is needed, because understanding MB is important and challenging.
    b. Education needs of the future workforce (data and curriculum integration) need to be identified and developed.
    c. Current tools and methods were not designed to comprehensively address impact, tradeoffs, and technology gaps in the circularity of polymers, especially beyond the boundaries of individual businesses within the supply chain. To fully assess the multiple dimensions of performance, value and impact of circular polymers, substantial investment at the interface of materials science, chemistry, engineering, economics, and data science are critically needed.

Based on these findings, NIST has seven recommendations for the application of MB to certify circular polymers:

1. Establish clear, prioritized technological, environmental, social, and economic goals for transitioning towards a circular economy for polymers.
2. Adopt a national strategy for the implementation of rigorous MB accounting methods for circular polymers, aligned with achieving the prioritized goals in recommendation 1.
3. Establish processes and frameworks that promote successful expansion of collection, capacity, and markets for both mechanically and chemically recycled polymers.
4. Develop open, consensus-based standards for certification methods and tools that are transparent, require interoperability or reciprocity, and are available to the entire supply chain.
5. Establish transparent, auditable data, data standards, and a framework suited to the needs and integrity of the entire supply chain.
6. Align definitions, terms, and methods necessary for standards harmonization, interoperability, and broad adoption.
7. Invest in a multidisciplinary research and development program at the interface of polymer science and engineering, manufacturing, economics, and data (privacy, sharing, and access) to enable manufacturing innovation, stronger decision making, and improved education and communication tools, and to improve supply chain integrity and accountability for circular polymers.

SOS 2.0 also tasked NIST with "an assessment of the environmental impacts of the full lifecycle of circular polymers, including impacts on climate change." Through the course of our research in preparation for this report, we concluded that there is not sufficient information to make comprehensive assements of this nature. There are many communities investigating various aspects and stages of the supply chain, from resource extraction/feedstocks to molecular design, formulation, product design, consumption patterns, collection infrastructure, reprocessing strategies etc., as well as the environmental impacts of polymers lost to the environment, and the (socio)economic cost-benefit analyses of polymers. None of these communities has a comprehensive, translatable, or transferable view of the full lifecycle. The data used in these studies are often not publicly available. Many studies are not reproduced, or outcomes are rooted in subjective criteria which have not been broadly adopted by large communities. Thus, there is a profound need for measurement and terminology consensus, broader and deeper data sets which are findable, accessible, interoperable, and reusable, as well as convening bodies to engage the wide range of social and technical disciplines and stakeholders to identify common understanding of the tradeoffs and priorities in this sort of analysis. We believe that an agency like NIST, with its core research programs, deep expertise in all these disciplinary interfaces and a mission aligned on both economic security and quality of life, is uniquely positioned to provide technical leadership in this endeavor in coordination and collaboration with others within federal, state, and local governments, but it will require significant investment of time and resources.

List of Acronyms

B&C	Book and claim
BTU	British thermal units
CGF	Consumer Goods Forum
CoC	Chain of custody
EoL	End of Life
EPA	Environmental Protection Agency
EU	European Union
FSC	Forest Stewardship Council
FTC	Federal Trade Commission
GHG	Greenhouse gas
HDPE	High density polyethylene
IP	Identity preserved
ISCC	International Sustainability and Carbon Certification
ISEAL	International Social and Environmental Accreditation and Labeling
ISO	International Standards Organization
LCA	Lifecycle assessment
LDPE	Low density polyethylene
LHV	Lower heating value
LLDPE	Linear Low-Density Polyethylene
MB	Mass balance
Mt	Million metric tons
PA	Polyamide
PC	Polycarbonate
PCR	Post-consumer resin
PEF	Polyethylene furanoate
PET	Polyethylene terephthalate
PHA	Polyhydroxyalkanoate
PLA	Polylactic acid
PP	Polypropylene
PS	Polystyrene
PUR	Polyurethane
PVC	Polyvinyl chloride
RED	Renewable Energy Directive
RMS	Recycled Material Standard
RSB	Roundtable on Sustainable Biomaterials
RSPO	Roundtable on Sustainable Palm Oil
SG	Segregation
UL	Underwriters Laboratories

Table of Contents

1 Background

This section describes:

- The current state of the global use of plastics, their role in the economy, and the problems introduced through their use;
- Potential solutions, methods for recycling of plastics, and the dilemma surrounding accounting for recycled plastic content in end products; and
- The approach NIST used to identify challenges in deploying MB accounting. Standardized approaches to MB accounting would enable more credible marketing of recycled content in end products fostering more adoption of the approach.

1.1 The Problem: Current State of Plastics Economy

The word 'plastic' technically refers to a material that can be softened and reshaped by applying heat without losing other properties, but over the last century the word has become the common term for a category of synthetic organic polymers that have become essential to modern life [10]. Due to their many useful, tailorable properties and applications, plastics are used in a variety of industrial sectors including packaging, construction, automotive, electronics, textiles, household items, healthcare, and toys [11]. There is no question that human health, comfort, and convenience have been vastly improved by plastics and that the low functionality, and environmental impact of plastics exceeds that of many alternative materials.

In 2019, global plastics production reached 368 million tonnes, a 2.5 % increase from the year prior [12]. The vast majority of plastics produced today are derived from fossil fuels, and global production – feedstock and processing energy combined – represents around 8 % of annual oil and gas consumption [13]. This has been projected to increase, however, as plastics are estimated to become the biggest source of new demand for oil over the coming decades, and in some projections, the only source [14, 15]. The United States in particular is a major producer and consumer of plastics, representing 19 % and 21 % of global plastics production and consumption, respectively [16, 17]. Further, the North American region has the highest per capita plastic consumption in the world at 306 pounds per capita per year [16].

Figure 1 displays a plastics flow diagram of the accumulated volume of plastics produced between 1950-2015 [18, 1]. Plastic packaging constitutes the largest market for plastics, representing nearly 40 % of demand, more than double that of building and construction, the next leading sector. As a result, the majority of plastics manufactured today are commodity thermoplastics (90 %), which include high, low, and linear low-density polyethylene (HDPE, LDPE, and LLDPE) (34.4 % combined), polypropylene (PP) (24.2 %), polyvinyl chloride (PVC) (16.5 %), and smaller percentages of polystyrene (PS), polyethylene terephthalate (PET), engineered plastics, and high-performance polymers [19]. While these plastics share common fossil derivatives, their production and processing also includes a variety of added chemical substances, including additives to help maintain, enhance, and impart specific properties (e.g., antioxidants, plasticizers, flame retardants), processing aides to enable or ease the production or processing of plastics (e.g., polymerization catalysts, solvents, mold release agents), and non-intentionally added substances including byproducts, breakdown products, and contaminants [11, 20, 21, 22, 23, 24, 25]. In fact, a recent investigation revealed the use of more than 10,000 chemical substances in plastic product formulation, only a fraction of which have been widely studied and many of which are known as substances of potential concern [11]. Many of these substances are not chemically bound to the polymer matrix and, therefore, have the potential to be released throughout the lifecycle of the plastic.

The extensive plastics economy has resulted in significant challenges at end-of-life (EoL), particularly in recovering and retaining the economic and technical value of the materials. As shown in Figure 1,

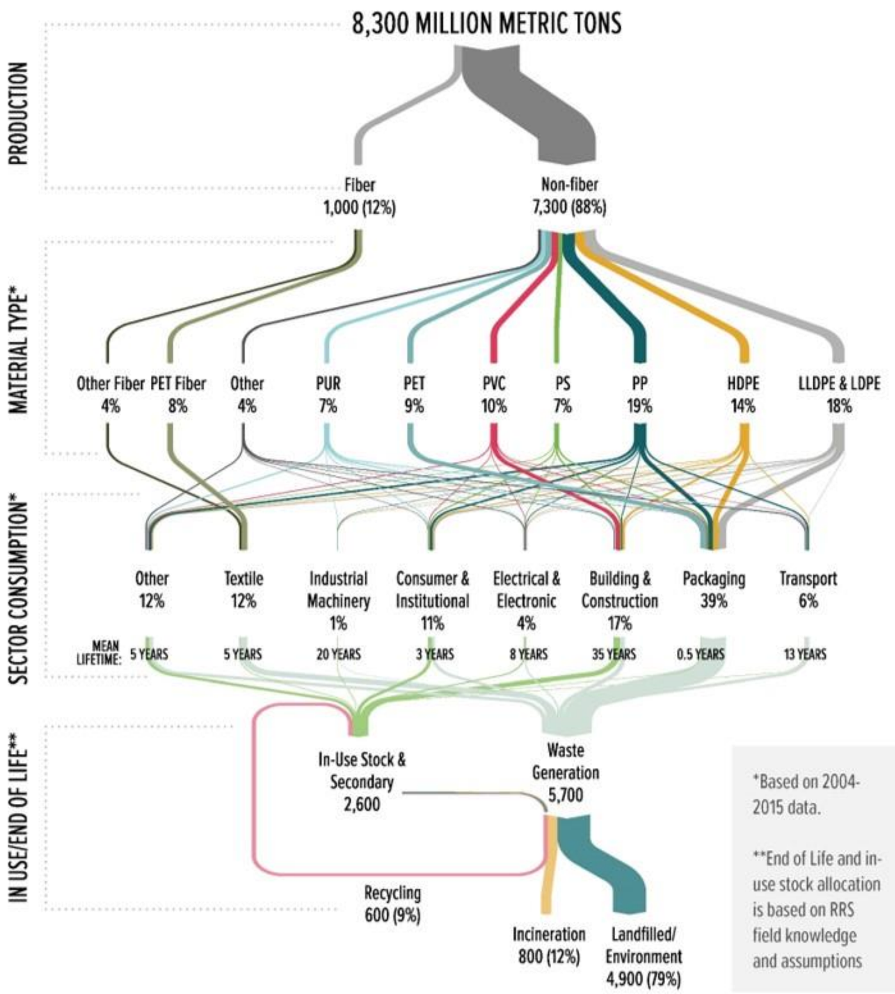

Figure 1: Production, use and fate of all plastics ever made, 1950-2015 (used with permission from RRS (Resource Recycling Systems, Inc.) [18, 1])

an estimated 79 % of all plastic waste generated between 1950-2015 (4900 of the 6300 million metric tons, Mt generated) has been discarded in landfills or the natural environment, 12 % was incinerated, and a mere 9 % has been recycled through mechanical recycling processes [1, 18]. The annual plastics recycling rate in the United States also hovers around 9%, although the rate is higher for specific plastic container types (e.g., in 2018 the recycling rate of PET bottles and jars was 29.1 % and that of HDPE natural bottles was 29.3 %) [2, 3]. In effect, ≈70 % of recyclable PET and HDPE packages are lost to landfills or the environment, representing a significant environmental and social impact as well as loss of economic value.

Interest in plastic waste has grown in recent years as an increasing body of research provides evidence of the distribution and concentration of unmanaged plastic debris in the natural environment (e.g., marine pollution, airborne particles, plant uptake) as well as ingested by humans, animals, and organisms (e.g., [26, 27, 28, 29, 30, 31, 32, 33]). Furthermore, global trade disruptions have exacerbated the issue, causing a fundamental reevaluation of the existing infrastructure and markets, both domestic and global, for plastic waste recovery, and methods to improve retention of materials in the economy. Gaps remain in the research, particularly focusing on sources and scalable solutions to plastic waste generation [34, 35]. As such, a need is emerging for better understanding of how plastics, and particularly packaging, can be better recovered and recycled at EoL.

1.2 The Response: Recycling and Mass Balance Accounting

While reducing and reusing plastic products and packaging will have a positive impact, a circular economy for plastics must incorporate recycling as a major lever for addressing plastic waste. Plastic materials can be recycled in a variety of ways; however, the ease and economics of recycling varies among polymer types (i.e., resin codes), package designs, product types, and product designs [13]. Mechanical recycling is the predominant approach to plastics recycling in the United States. and elsewhere. The process typically includes separation and sorting based on shape, density, size, color, or chemical composition, followed by washing, grinding (i.e., size reduction), compounding, and pelletizing prior to conversion to new plastic products or packaging [36]. Mechanical recycling has several limitations; among them are supply challenges resulting from consumer behavior (e.g., participation in recycling) and access to recycling services – a key challenge shared with chemical recycling. However, several regulatory, technical, and economic challenges also constrain mechanical recycling, including:

- the complex and evolving waste stream;
- progressive degradation of some plastics subjected to multiple processing cycles;
- incompatibility of polymer types due to immiscibility at the molecular level;
- difficulties removing colorants, additives, odors, and residues;
- reduced key performance properties which limit addressable applications; and
- regulatory restrictions in food, pharmaceutical, and medical applications which are difficult for mechanically recycled polymers to meet [9, 37, 36, 13, 38].

Some of the technical challenges may be lessened with more investment in research and technology; however, more needs to be done to rapidly expand the volume of circular polymer flows. As a result, interest in chemical recycling has grown steadily as a means to overcome the technical limits of mechanical recycling and increase plastics recycling for polymers, specifically targeting difficult to recycle plastics. In general, chemical recycling involves additional chemical processes, some of which break molecular bonds which can reduce polymers to their original monomer (among other things) unit to allow for re-polymerization and use in new plastic materials. Indeed, chemical recycling faces the same social challenges as mechanical recycling, namely consumer/municipal participation in recycling. However, chemical recycling allows for the processing of more diverse and mixed sources and should enable indistinguishable performance for prime materials at high levels of recycled content. The process can also generate other valuable petrochemical feedstocks including monomer precursors (e.g., fuels, naphtha). Multiple chemical recycling processes exist for plastics and generally fall into three categories:

(1) Purification, where plastic is swollen or dissolved in a solvent, separated, and purified to extract dyes and additives to obtain a 'purified' plastic. This process does not change the polymer at the molecular level. Typically used for PVC, PS, and polyolefins.

(2) Decomposition (also called depolymerization), where the molecular bonds within certain types of polymer chains are broken by biological, chemical, or thermal means to revert to the monomer blocks forming the polymer. Monomers can be either single molecular repeat units or multiple repeat units bound together called "oligomers" both of which can be reconstructed into plastics. This process is used for PET, PUR, PA, PS, PLA, PC, PHA, and PEF.

(3) Conversion, where the plastic is heated in the presence of oxygen (gasification) or without oxygen (pyrolysis) and the plastic waste is turned back into the different molecules forming hydrocarbon chains (can be used on mixed plastic streams and is similar to cracking processes in petroleum refining) [39, 40].

Figure 2 presents the hierarchy of recycling technologies in a circular economy for plastics with respect to where the atoms and/or molecules would reenter the supply chain. Many consumer brands have committed to ambitious recycled content targets, aiming to support a circular economy and reduce plastic waste (e.g., [41] [42] [43]). Existing mechanical recycling infrastructure alone is not currently capable of supplying the quality and quantity of recycled material needed to meet goals being set by some brand owners and non-U.S. national policies. Still, by some estimates the capacity of the mechanical recycling market could more than double. With additional research to solve some material and processing challenges, it could expand further. There is unmet demand for mechanically recyclable feedstocks, and it has some attractive benefits relative to other routes, including lower energy intensity processing, higher conservation of material masses within the polymer loop, and long-term use of recovered material in durable goods applications.

Many stakeholders believe that, even with innovation and expansion of capacity and collection infrastructure, mechanical recycling alone will not be able handle the full range of plastics waste. To address the problem more fully, society will need complementary methods that are more intensive, and able to recover value from more diverse polymer types and product formats, hence the interest in chemical pathways to return molecules in various forms to the supply chain. There have been a large number of 'green field' construction projects announced in the United States that are advertised as relying solely on recycled polymer streams to produce new feedstocks, though it is unclear if the collection infrastructure will be able to supply large enough volumes to support their operation in the near term. Some companies are interested in incorporating recycled polymers with virgin feedstocks using existing assets, thus eliminating the need for new, capital intensive infrastructure dedicated to recycled polymer processing. However, while some chemical recycling processes may use existing infrastructure, this infrastructure is not designed for these feedstock streams, therefore extensive capital investments may still be required to retrofit or build new facilities. Furthermore, relative to the scale of chemical production at these facilities, the initial fractions of recovered polymers fed into them is expected to be small. Therefore, to maximize the incentive to use recovered polymers and to increase their use, chain of custody approaches such as MB accounting are used to enable stakeholders to use these assets and to overcome efficiency and cost barriers.

Once recovered polymers are mixed with their virgin counterparts and chemically reprocessed, they are, in principle, indistinguishable from one another. This mixing of recycled and virgin inputs poses a challenge in the accounting for recycled content in the output of plastic products and packaging, particularly in the case of chemical processes. During chemical processing, complex, competing

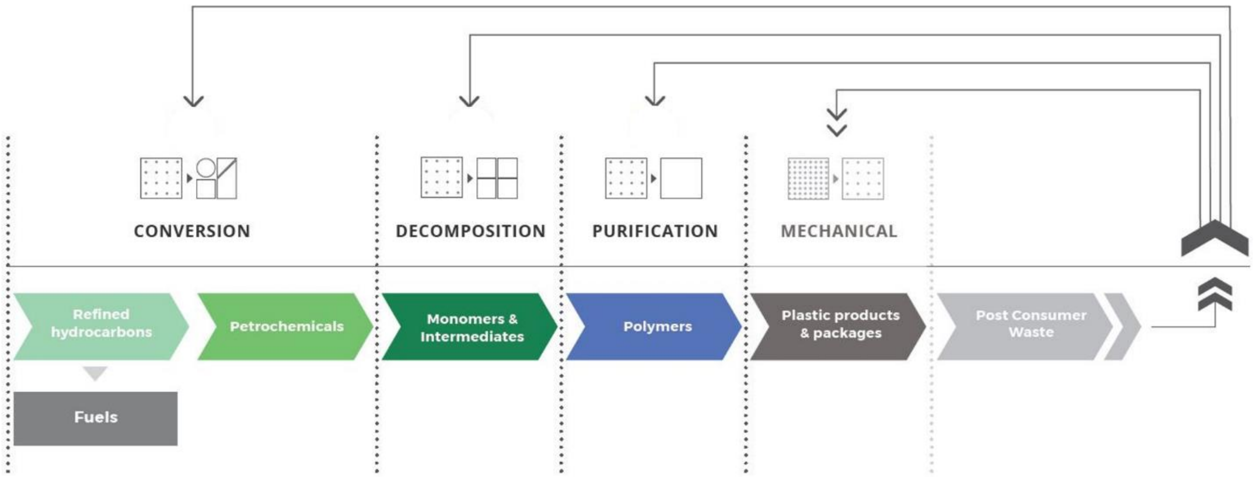

Figure 2: Recycling technologies to enable a circular economy of plastics (adapted from ref [40]).

chemistries produce multiple products that may ultimately find their way into multiple supply chains (e.g., fine chemicals, personal care, or fuels in addition to polymer manufacturing). As a result, MB accounting has been proposed and employed as a tool to trace, track, and certify circular content in polymers.

In effect, MB is a tool used to incentivize shifts in the supply chain to support more sustainable and environmentally beneficial technologies or capabilities that are initially economically disadvantageous. MB is widely used in other commodity sectors, including timber, agriculture (food and cotton), and biofuels. It is now being considered in the polymers sector due to 1) its success in other markets and 2) the opportunity to accelerate the advancement of chemical recycling specifically where differentiation of output products by the input material streams is both difficult and inefficient. The application of MB for plastics originated in Europe and is seeing increasing adoption in the U.S. Further, emerging attention and policy proposals at the state and federal level (e.g., [44] [45] [46] [47]), combined with increased brand commitments have spurred interest in MB as a means to facilitate polymer recycling in the United States, even though concerns remain regarding quantification of the net environmental impacts of the approach.

One such federal initiative is the Save Our Seas 2.0 Act, signed into law on December 18, 2020. The Act is composed of three broad components: (1) strengthen the U.S. domestic marine debris response capability, (2) enhance global engagement to combat marine debris, and (3) improve domestic infrastructure to prevent marine debris. Section 134 of the Act tasks the National Institute of Standards and Technology (NIST) with performing a study on MB methodologies to certify circular polymers. Specifically, the study shall include "an identification and assessment of existing MB methodologies, standards, and certification systems that are or may be applicable to supply chain sustainability of polymers, considering the full life cycle of the polymer, and including an examination of (A) the International Sustainability and Carbon Certification [ISCC]; and (B) the Roundtable on Sustainable Biomaterials [RSB]" [45]. The two identified organizations represent existing certification programs that use MB accounting to certify circular polymers.

1.3 The Challenges: Stakeholder Perspectives

To respond to the MB assessment, NIST hosted a virtual workshop entitled "Assessment of Mass Balance Accounting Methods for Polymers" on May 3-5, 2021. The purpose of the workshop was to convene stakeholders associated with MB methodologies, including existing standardization and certification programs focused on circular polymers as well as other, comparable industries. Participants included representatives associated with brand owners, chemical/polymer manufacturers (e.g. resin producers), converters, the mechanical recycling industries, third party certification bodies, and consumer interest groups. Through presentations and discussions, participants helped to identify and assess existing MB methodologies, standards, and certification systems that are or may be applicable to assigning recycled content in the supply chain of polymers. Further, the workshop aimed to assess challenges, including any legal or regulatory barriers, to developing a standard and certification system for circular polymers. This report summarized the workshop outcomes and provides recommendations for advancing MB for circular polymers.

Workshop planning and organization involved outreach to stakeholders to identify core areas of interest. The resulting agenda included three plenary presentations and six topic-specific sessions:

- Definitions,
- Allocation,
- Multi-Site Claims/Credit Transfers,
- Certification Requirements & Interoperability,
- Legal & Regulatory Barriers/Support, and
- Consumer Awareness.

Each session included a presentation by an expert on the topic, followed by a breakout discussion in which participants were randomly assigned to virtual roundtables. NIST facilitators led discussions based on prepared questions. The plenary presenters included an industry expert on MB accounting for polymers, an EPA representative, and a panel of existing MB certification organizations. In total, the workshop brought together approximately 100 participants including 12 speakers. The workshop agenda and participation list are provided in Appendices A and B, respectively.

2 Mass Balance Overview

MB is one of five common chain of custody (CoC) models designed to create transparency and trust throughout the value chain regarding properties of goods and materials that are otherwise difficult to distinguish [48]. Such properties include origin, raw material composition, and production practices. The CoC models are commonly applied to trace sustainably and/or ethically produced/processed materials that are not identifiable compared to their counterparts. The five CoC models shown in Figure 3 share the common objective of guaranteeing solid bookkeeping and corroborating a link between the input with specific characteristics (e.g., sustainable, recycled, organic) entering the production system and that of the out-going product [49]. The models differ in how they manage and record that link, and the set of rules for mixing, balancing, and tracking.

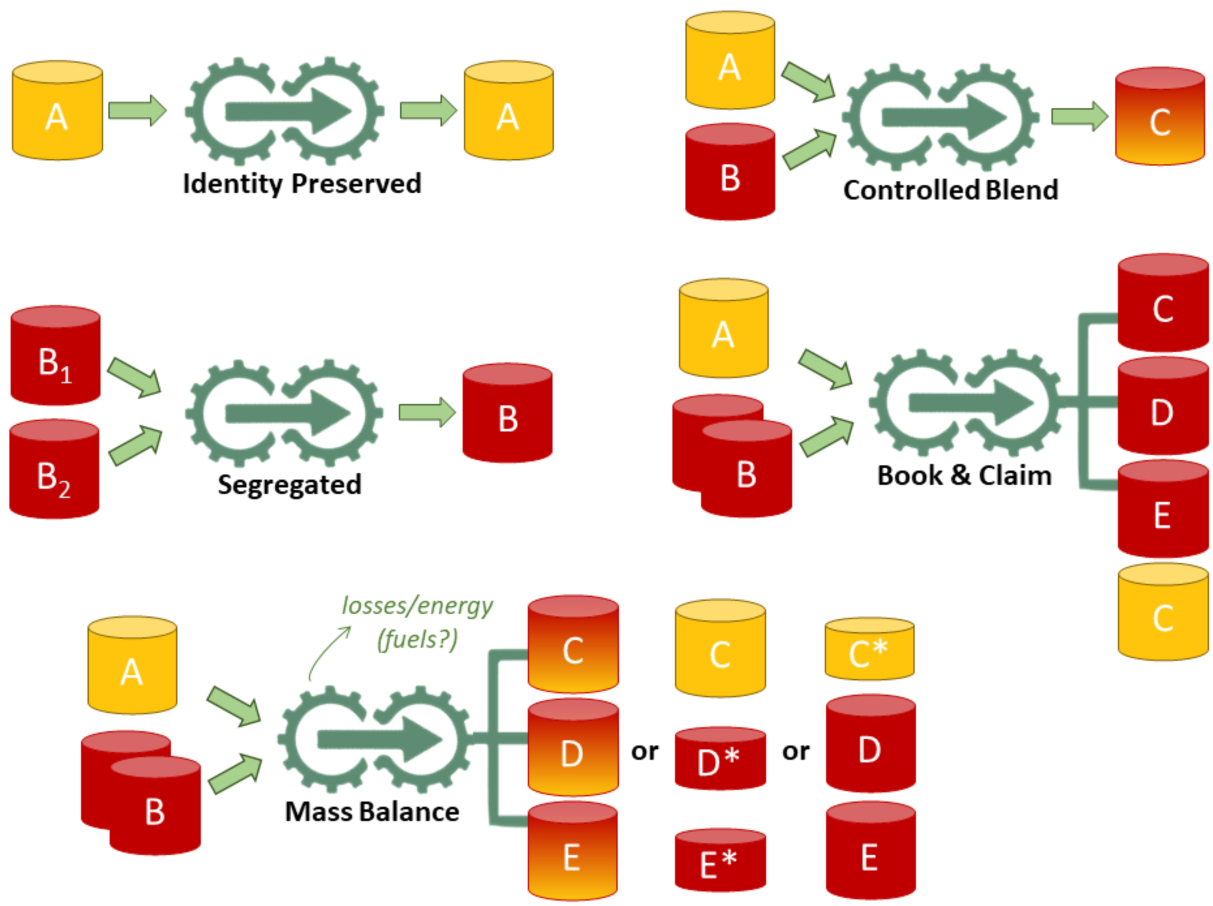

Figure 3: Five common chain of custody models. * Represents where credits or allocation can be adjusted for losses in the MB approach.

In the identity preservation model, inputs originate from a single source and the material or product is kept physically separated and its characteristics are maintained throughout the supply chain [48]. One example would be a specific palm oil that can be traced back to a single farm with other oils. The segregation model consists of the aggregation of products of identical origin or produced according to the same standards. In this model, materials from different sources can be mixed within a common category, but material categories are kept physically separate (e.g., certified organic food).

In the controlled blending model, materials or products with a set of specified characteristics are mixed according to certain criteria with materials or products without those characteristics [48]. The result is a known proportion of specified characteristics within all parts of the final output because the “ratio between inputs is known for all outputs at all times for a contained volume (e.g., batch, shipment, storage facility)” [48]. Other CoC reference documents (e.g., [50]) consider the controlled blending model to be synonymous with site-level MB in which materials with and without the specified characteristics remain segregated until the manufacturing or processing stage in the supply chain, when the material streams with and without characteristics are mixed, and the proportions of product with characteristics (e.g., certified) at the overall site level are recorded and reconciled. In either case, the blended content is controlled and known for all batches of material produced.

In the MB model, materials or products with specified characteristics are mixed with materials or products without the same or all of the same characteristics, resulting in a claim on a part of the output, proportional to the input [48]. Either a Rolling Average Percentage method or Credit method are typically used as defined in ISO 22095:2020, “Chain of custody — General terminology and models.” MB is designed to track the total amount of desired content (e.g., recycled feedstock) through the production system and ensure an appropriate allocation of this content to the output product based on auditable bookkeeping. A key characteristic of MB model is that the physical presence of the desired characteristic in the product is low or unknown. MB is best suited when the volumes or values of goods or materials from desired sources are too low to be shipped, stored, or processed separately or the technical process does not allow for differentiation.

The book and claim (B&C) model is a fully administrative model applied when there is not a physical connection between the certified supply and the final product (e.g., renewable electricity). As represented by the “C” output in the Book and Claim representation in Figure 3, credits are issued when materials or products enter the market and may be traded and sold independently of the physical delivery of those materials or products [48].

Historically, CoC systems have been developed for organic farming, fair trade, and sustainable food production. MB specifically has been used in various commodity sectors by different certification organizations for the last several decades. For example, the Forest Stewardship Council (FSC) has certified sustainable timber using MB since 1993, the Better Cotton Initiative has certified cotton since 2005, the Roundtable on Sustainable Palm Oil (RSPO) has certified palm oil since 2004, the Roundtable on Sustainable Biomaterials (RSB) has certified biofuels since 2007, and Fair Trade has certified tea, cocoa, and sugar using MB since 1997 [49].

MB allows for integration of feedstock from recycled plastic sources along with conventional fossil feedstock. To account for recycling, credits are produced when recycled raw materials are consumed and based on the mass entering the system. Credits are then decoupled during the production process (e.g., undergoing steam cracking) and reassigned to physical materials and applied to outgoing products. Credits are managed using a digital inventory, and conversion factors are used to reflect actual operating yields, losses, and bills of materials. As a result, credits can be based on different units depending on the material and process (e.g., mass, energy, or greenhouse gas (GHG) equivalents). To support a credible marketplace, internationally recognized third-party certification methodologies are applied to certify attributions in the reported outputs are traceable in the inputs of the system using an auditable systematic approach.

During the workshop, many polymer industry representatives expressed support for MB to aid in a transition to the circular polymer economy as a cost-effective strategy to expand markets for both mechanical and chemical recycling, particularly where mechanical recycling is limited (e.g., mixed plastics streams, contaminated feedstock). That said, the circular economy is an evolving system of manufacturing, and chemical recycling itself is still developing. Therefore, the broadly accepted criteria for defining MB principles and practices are yet to be established, and a lack of common goals in applying circular principles is a barrier to informing common MB standards for polymers.

2.1 Current Mass Balance Certification Programs

The use of MB in the polymer industry was initiated in the European Union (EU) as a means to meet voluntary commitments and initiatives (e.g., [51, 52, 53]). Therefore, most certification programs using MB were developed in Europe. Currently, six voluntary certification programs use MB to certify recycled polymers, as displayed in Table 1. ISCC Plus, UL 2809, and RSB's Standard for Advanced Products have the largest presence in the United States at present. GreenBlue's Recycled Material Standard was still under development at the time of the workshop and has since been finalized [54]. REDCert[2] was developed for, and primarily operates within, the EU to offer certification in accordance with the EU Renewable Energy Directive in combination with other European regulations [55]. The Ecoloop certification is a relatively new certification (launched 2018) run by Ecocycle GmbH in Germany and is also focused on the EU market.

Due to their established history and/or applicability to the U.S. market, representatives from ISCC, UL, RSB, and GreenBlue were invited to participate in the plenary panel in the workshop. In addition, a representative from the FSC participated to discuss the application of MB in the certification of sustainable timber. Representatives introduced their standard, explaining the history of development and differentiating features and focus areas.

ISCC is likely the largest of the certification systems in terms of the number of certified companies and products with more than 4900 certificates in over 100 countries, with approximately one-third of certificates being held outside of Europe. They aim to support a circular economy and bioeconomy with broad raw materials and products coverage, and they offer different CoC options and associated training programs. ISCC offers certification for mechanical and chemical recycling, for segregated supply chains, as well as with and without the use of the MB/allocation approach. Key MB principles under ISCC include independent third-party certification across entire supply chains, clear CoC rules, identification of raw material categories, a defined boundary (geographical, temporal), rules for determination of site-specific sustainable yield and their allocation, clear verification and reporting of volumes to stakeholders, and verified claims towards customers and consumers (i.e., claims must reference MB approach).

RSB is a global, multi-stakeholder organization that aims to drive the development of a bio-based and circular economy. The RSB Advanced Product Standard is an umbrella standard covering three product categories: bio-based products, products with recycled content, and products produced in complex chemical production settings where MB and attributional approaches are needed. The RSB standard is based on impact-related claims: claims that reflect the fossil resources substituted, GHG emissions reduced, and sustainable production across the entire supply chain. The standard requires that sustainability attributes are met across the supply chain and ensures that the transition to sustainable materials does not add pressure to natural resources. The standard mandates the calculation of GHG emissions across the supply chain and requires the threshold of 10% emission reduction compared to the (virgin) fossil reference product. The MB and attribution approaches in the standard was developed on a life cycle assessment (LCA) basis. The standard was developed on

Table 1: Certification/Standards that Apply MB for Polymers

Certification/Standard	Status	Description & Governance Organization
ISCC Plus	Existing	Offers solutions for the implementation and certification of sustainable, deforestation-free and traceable supply chains of agricultural, forestry, waste and residue raw materials, non-bio renewables and recycled carbon materials and fuels. Governed by the ISCC Association. (Reference documents [56, 57, 58]).
Standard for Advanced Products (Non-energy use):	Existing	Focused on both bio-based and recycled material-based products that are produced in segregated supply chains and products that are produced in combination with fossil feedstock. Strong emphasis on sustainability with minimum requirements for greenhouse gas (GHG) reduction. Governed by RSB. (Reference document [59]).
Ecoloop	Existing	Certification for plastic producers, recyclers as well as processors and manufacturers of plastic products. Focuses only on recycled plastics. Governed by the company Ecocycle. (Reference documents [60, 61, 62, 63]).
REDcert[2]	Existing	Originally launched for food and feed in 2015, extended for material use within the chemical industry in 2018, and revised in 2019 to also include recycled materials from fossil sources. Governed by REDcert. (Reference documents [64]).
UL 2809: Environmental Claim Validation Procedure (ECVP) for Recycled Content	New/Emerging	Standard to evaluate the amount of recycled content in products including post-consumer, pre-consumer (post-industrial), closed loop, and total recycled content. Governed by Underwriters Laboratories (UL). (Reference document [65]).
Recycled Material Standard (RMS)	New/Emerging	Voluntary, market-based framework that enables consistent labeling of products and packaging that contain or support verified recycled material, either through a certified chain of custody or via the Attribute of Recycled Content (ARC) certificate trading system. Governed by the non-profit organization, GreenBlue (Reference documents [66, 67]).

a consensus basis in line with the approach of the International Social and Environmental Accreditation and Labeling (ISEAL) standard setting code [50].

Underwriters Laboratories (UL) has developed standards for product safety since 1903; UL 2809 provides a framework for the evaluation and validation of 'Defined Source' material content claims in manufactured products. *Defined sources* include recycled content, byproduct synergy, reused components, refurbished components, ocean plastic, and biomass sources of materials. As such, UL 2809 reaches beyond plastics and includes inorganics (e.g., metals) as well. Content claims in products are based on one or more of the chain of custody models as described in ISO 22095. When using MB, UL adds to the claim language that an allocation system was used in determining content. In developing the MB protocols, UL followed guidelines set forth in the International Organization for Standardization (ISO) standard 22095 [48] as well as a white paper published by the Ellen MacArthur Foundation [49].

GreenBlue is a nonprofit organization dedicated to the sustainable use of materials in society. They recently developed the Recycled Material Standard (RMS) to serve as a voluntary, market-based tool to address challenges faced when incorporating recycled content in packaging and products. The RMS is a framework standard that covers all types of materials with individual modules for specific materials (e.g., plastics). The plastics module covers both post-consumer and post-industrial plastic waste and includes segregation, MB, and B&C methods. The MB system offers a unique compromise between a strict proportional allocation approach and a more liberal free allocation approach with the "RMS compromise: non-proportional allocation with a deduction for fuels" (see Section 2.4). Standard development was a 2.5-year process, consensus-driven with subcommittees and public comment, and also followed ISEAL guidelines [65].

The FSC was established in 1993 to promote environmentally sound, socially beneficial, and economically prosperous management of the world's forests. The original standard was a simple, single CoC standard in which timber from a certified forest could be modified, manufactured, and sold as FSC-certified. The current standard is more complicated, includes a trademark licensing agreement, and has more than 50,000 certified companies including retailers. The current FSC standard includes an MB approach and acknowledges post-consumer as well as pre-consumer (sometimes referred to as post-industrial) reclaimed inputs. It also includes a percentage system such that if a minimum of 70 % FSC or post-consumer recycled content is used in a product (e.g., chair or table), that product can be labeled as FSC-mixed. Recently, FSC expanded both the credit and percentage systems to expand between multiple physical sites. For the credit system, each site must have at least 10 % FSC material in their credit account. For the percentage system, each site must have at least 50 % FSC at that physical site. FSC is piloting the expansion to different countries where companies with facilities in both countries (e.g., the United States and Canada) can share credits.

2.2 Different Approaches to MB Certification for Polymers

The need for clearly defined terms and concepts is imperative in MB certifications. The above-mentioned ISO 22095 [48], outlines general properties, implementation methods, and supply chain requirements for each CoC model. Many terms specific to MB are not defined, however. An ISO technical committee (ISO/TC 308 [68]) is currently enhancing CoC documentation, with a specific focus on the development of MB and B&C standards.

Several terms/concepts discussed in the workshop that are currently undefined or controversial among the industry include the following:

- **System boundary:** Chemical recycling of plastics often generates multiple chemicals, which can be sent to different facilities for further processing and utilized in various end products. Further, many large chemical companies have multiple facilities spread across geographic regions. As a result, defining a uniform system boundary for performing MB is yet undetermined, and current certification programs differ in this regard. Questions remain about establishing limits or guidelines in defining a system boundary.

- **Credit Units:** When materials enter the chemical recycling system the mass of material is transformed into credits using a stated unit conversion. Typical conversion and unit examples include mass (metric tons), Lower Heating Value or LHV (calorie, BTU, tons of oil equivalent (toe), or Joule), and molecular unit (moles, mass, number). Units can be specific to the transformation within the given system; however, the system cannot use multiple credits. Therefore, credits are effectively the currency of MB and, just like each country has a unique unit of currency, each MB system can have a unique credit unit. This can be a cause of complexity and confusion among stakeholders and consumers and may be a barrier to interoperability across certification systems unless calibrations or conversion principles are established.

- **Connectivity and Traceability:** Chemical recycling operations allow for chemical as well as physical connectivity, and thus associated traceability. However, not all facilities have physical connectivity. For example, one facility may have all branched operations in which pipes connect operations such that recycled content entering the system could physically and chemically be in all outgoing products. Another facility may operate units in parallel, with no physical connection between sets of processes. Once chemically converted, recycled and virgin organic molecules, including polymers, are identical. Therefore, recycled content could have been in all products, but physically they are separated (not connected by pipes). ISO 22095:2020 defines traceability as the “ability to trace the history, application, location or source(s) of a material or product throughout the supply chain” [48, p. 6]. However, the consideration of physical versus chemical connectivity is affected by different perceptions and viewpoints regarding this definition.

- **Proportional versus Non-Proportional Allocation:** The assignment of credits to end products can be either proportionally or non-proportionally allocated. Proportional allocation means that the number of available credits is split according to yield or distribution. Non-proportional allocation allows available credits to be freely attributed amongst end-products, i.e., it allows companies to allocate content to where it is most valued and needed in the market. In principle, under non-proportional allocation, 100 % of credits could be attributed to a single product stream and 0 % to the other product streams even though recycled content is distributed throughout all product streams. The terms allocation, attribution, and assignation are used somewhat interchangeably in discussions on this topic.

- **Balancing Period, Reconciliation Period, and Accounting Period:** In accounting, reconciliation is the process of ensuring that two sets of records (e.g., the balances of two accounts) are in agreement. In MB, reconciliation is used to ensure that the number of units (e.g., mass, joules) leaving the system (i.e. in end products) matches the actual units entering and used in the system. This is done by making sure the balances match at the end of a particular accounting period. Under current certifications, typical MB balancing periods are 1, 3, or 12 months (with three months being the most common). For example, in the UL program, results are typically audited in monthly tranches within a yearly accounting period, but ISCC Plus certifications typically use a three-month balancing period. Results are reconciled at the end of the Accounting Period for both the Accounting Period and each of the monthly tranches. Each certification program handles this differently, and debate ensues regarding the appropriate minimum and maximum balancing, accounting, reconciliation period, credit lifespan (if any), and whether credit accounts should be permitted to go below zero.

- **Post- Consumer versus Post- Industrial Recycled Material:** Post-consumer recycled material refers to any material or finished product that has served its intended use and has been diverted or recovered from waste destined for disposal [69]. Post-industrial recycled material generally includes scrap or other waste generated by a manufacturing process. Typically, the latter is cleaner and potentially can be used again for the same purpose (e.g., PET scrap from bottle manufacturing can be melted and used again in bottle-making, multi-layered snack food packaging cannot). While collection and recycling of both post-consumer and post-industrial material contribute to reducing waste in the environment, debate continues about which streams should be included in MB. Chemical recyclers would like to see the post-industrial materials included because it can be a cleaner, more reliable source while multiple stakeholders work to improve quality and quantity of post-consumer materials, and it may facilitate meeting targets for recycled content faster. Others argue that the focus should solely be on post-consumer to have the greatest impact on reducing plastic waste leakage to the environment.

2.3 Allocation

Chemical recycling processes break polymer molecules down into small (or at least *smaller*) molecules and then uses those molecules to make new and distinct products. The output products may consist of a range of materials derived from the inputs with new molecular constitutions such as PVC used in construction, PET used in fibers and packaging, and fuels. (See Figure 1.) The flow of input materials from different sources is expected to vary over time.

Allocation refers to the proportion of inputs (or feedstocks) assigned to specific outputs (or products). In other words, allocation describes how to account for the assignment of CoC claims to products. This is a key area where standards are needed to maintain consumer trust in MB by establishing rules regarding how to make claims in the market.

While allocation is a commonly accepted practice for accounting for recycled content in end products in principle, four general types of allocation methods with relevance to circular polymers are being considered:

- **Proportional:** This method is based on the assumption that recycled units flow the same way as non-recycled units and therefore have the same distribution among outputs. The certified (e.g., recycled) inputs flow to outputs in accordance with the yield in which they went in. For example, if 10 % of the input stream is comprised of recycled polymers, then 10 % of each output stream is considered to contain recycled content and credits must be allocated as such (Figure 4). This is the most straightforward allocation method, and it does not allow for flexibility in the credit allocation process. As a result, some argue that this approach may be too strict for certain markets and may in fact hinder the advancement of the industry by making it more difficult to meet recycled content goals in specific sectors, products, or brands.

Figure 4: Representation of Proportional Allocation [with permission from Laura Thompson [70]]

- **Non-Proportional (Free Allocation):** Many chemical processes produce multiple outputs, many of which may not have a market for recycled content. Non-proportional allocation allows for credits to be freely assigned to any product. For example, one output product can be allocated 100 % of the recycled content claims and the other products have no claim (Figure 5). This approach offers the highest degree of freedom and flexibility, but concerns arise regarding consumer understanding and trust. MB systems in other industries, such as FSC, RainForest Alliance, RSPO, etc., allow non-proportional allocation.

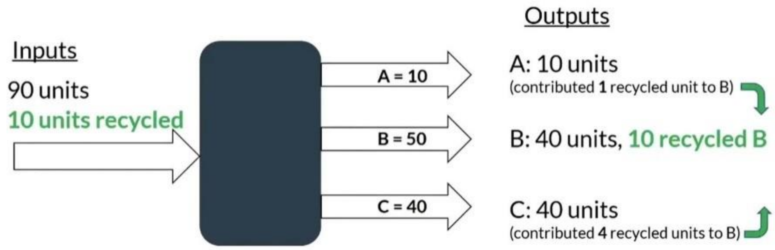

Figure 5: Representation of Non-Proportional Allocation [with permission from Laura Thompson [70]]

- **Non-Proportional – Fuel-exempt:** Some chemical recycling processes generate fuels as a product or by-product, a commodity that certain standards, such as RMS, does not recognize as a recycled material (i.e., not part of the circular economy). Therefore, the RMS standard allocates credits according to the "RMS compromise: non-proportional allocation with a deduction for fuels." Under this system, units directed to fuel cannot be counted to other products; recycled units are lost from the system regardless of whether the fuel is used on-site or sold as a product stream. For example, if product stream "C" in Figure 4 was a fuel (for example a diesel mixture or a fraction burned off in a heating process), the four recycled units would be lost from the system, and only 5 remaining units would be available for non-proportional allocation between the other product streams. This approach was recently described as "*Free Allocation – Fuels Exempt*" in a recent study by Eunomia Consulting [71].

- **Non-Proportional - Polymers only:** Under this allocation method, only outputs directly linked to the production of polymers can be freely allocated. As such, units to any non-polymer products or outputs are lost and cannot be applied to other products. For example, if product stream "A" in Figure 5 was not a polymer product (for example a small molecule or fine chemical being sold into the pharmaceutical industry), and stream "C" was a fuel, five recycled credits (one from A and four from C) would be lost from the system.

When using MB, the type of allocation method used for co-products is important. Existing standards for recycled polymers use different methods. ISCC Plus and RSB currently both allow for Free Allocation while RMS has adopted a compromise for chemical recycling with the Non-Proportional (Free Allocation) Fuels exempt method. The Polymers only methodology is not currently practiced but is under consideration in Europe for the Single Use Plastic Directive [72]. There is desire from multiple stakeholders along the supply chain to have harmonization between standards, such that materials could flow from one CoC to another, but that is not possible unless allocation methods are aligned and interoperable. Without alignment on allocation methods, corrective action is needed to harmonize. Otherwise, the system is vulnerable to either control of the marketplace by a single certifying body, or requirements to maintain certifications with multiple bodies in order to satisfy the needs of different customers. An example of this issue was raised during workshop discussions on sustainable timber traceability in the paper supply chain, in which the need to acquire and sustain subscriptions to multiple certification bodies was described as a barrier to participation, particularly for small and medium-sized businesses.

Controversy ensues over the most appropriate allocation methodology that supports an industry transition and is also understandable and acceptable to consumers. Properly accounting for system losses, fuels, and other co-products is complicated given the complex systems of chemical recycling. During the workshop, Free-Allocation was supported by the chemical industry representatives because it eases the complexity and lowers the economic barrier to investment. Proponents of non-proportional (free) allocation note that equipment that must be used was never designed for these recycled streams and will therefore produce some byproducts by necessity - and even if produced, these streams are salable or usable, and are therefore not increasing fuels usage - they are entering existing markets where they further displace virgin fossil feedstocks. However, non-governmental organizations (NGOs) and some brand representatives expressed skepticism of the credibility of the system. Divorcing credits from the physical material opens companies up to accusations of *greenwashing* (conveying the false impression of increased sustainability of products). Further, there was debate over whether MB standards, and allocation methods therein, can support both mechanical and chemical recycling, and without offering greater flexibility and advantage to one over the other.

The controversy over fuels is particularly fraught because this is considered by some NGOs and vocal opponents as being tantamount to releasing atoms and molecules to the atmosphere as gases, losing them from the system, and contributing to negative environmental impacts. Several prominent global multi-stakeholder forums (e.g., the Ellen MacArthur Foundation, U.S. Plastics Pact) have stated that plastics used for energy or converted to fuel is not considered recycling [49, 73]. Considering this, an implementation strategy could include a phasing structure. For example, one implementation strategy could allow free allocation initially to increase incentives, then phase in fuel exemption as the volume of recovered polymers increases. Alternatively, the strategy could initially require a fuel exempt allocation model, then allow for free allocation once carbon capture technology is implemented for complete recovery to balance out any emissions.

Given the nature of chemical recycling, the only way to truly account for whether and how much recycled content is found in the resulting products would be to have processing streams that only accepted recycled input (e.g., physical segregation). This solution is currently not an option because 1) it would not leverage existing facilities, 2) it would require greater transportation expense and associated environmental impacts to move recycled materials to the dedicated sites, and 3) there simply is not enough supply of recycled content in the United States right now to support/scale this type of separate infrastructure and the necessary expense that would be involved. Thus, some form of non-proportional allocation is necessary.

2.4 Multi-Site Claims/Credit Transfers

Sometimes recycled materials are present at one site but needed at a different site within the same company. Multi-site MB is an option to coordinate management of MB for multiple sites under the ownership and control of a single organization according to a set of qualifying conditions. As such, multi-site MB allows credits to be transferred digitally rather than requiring the physical movement of materials between a company's sites. For example, a company with parallel production systems in geographically different areas, one utilizing recycled content and the other using virgin content, can digitally shift credits from the site using recycled content to products made in the site without recycled content as opposed to physically transporting the products with recycled content to the region of the facility without said content. There are two primary motivations for multi-site MB: (1) sustainably move credits within the company's MB system boundary without producing the GHG emissions associated with physical transport, and (2) optimize the system as a whole and maximize scale by utilizing existing, but regionally imbalanced recycling infrastructure to support the global market demand for sustainable products. This would also allow for targeted infrastructure improvements to support specific operations rather than rely on a more challenging and uncertain broad investment to raise the recycling infrastructure quality more equitably across regions.

Multi-site MB requires qualifying conditions to ensure credibility. Currently, two structures exist in this effort. As displayed in Figure 6a, the MB system boundary can be drawn around multiple company sites, such that all MB accounting is performed within that boundary, i.e., one MB for the entire network. The second structure, displayed in Figure 6b, maintains a separate MB for each site and digitally transfers credits between the sites. This structure offers greater visibility when credit transfers occur as they are recorded as part of MB reporting requirements.

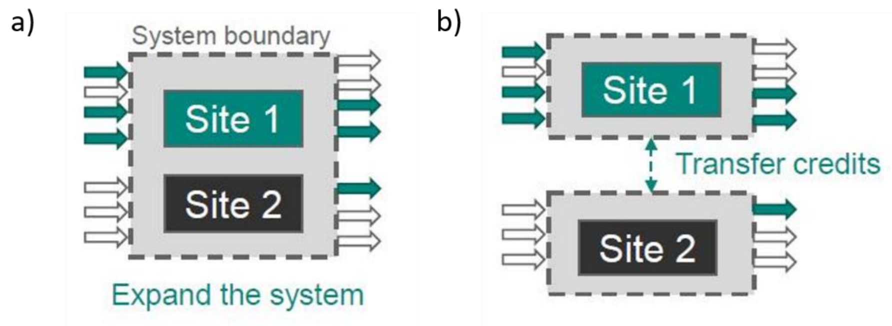

Figure 6: Structures of multi-site MB, a) one MB boundary including multiple sites, b) separate MB for each site with ability to transfer credits [with permission from Jason Pierce [74]]

Per the ISO 22095:2020 CoC definition, organizations can manage MB for continuous processes, a single site, or multiple sites (within a determined geographical area and timeframe) [48, p. 15]. As such, MB accounting can be performed via either a credit-based or a rolling average percentage method across single or multiple sites. The ISO technical working group (ISO/TC 308) is actively working towards standardized MB details on this topic.

Multi-site MB is used in certification standards in other commodity sectors such as Fair Trade cocoa and sugar, and FSC timber. Existing standards for recycled polymers use different approaches. Under ISCC Plus, MB is strictly site-specific, but credits can be transferred between sites under a set of conditions including: the supplier and recipient are part of the same corporate structure; sites are located within one country or neighboring inland countries; credits are applicable only to same kind of product; and both sites must be certified under ISCC Plus using the same certification body. Further, ISCC requires the use of multi-site MB be disclosed on Sustainability Declaration paperwork for products. UL 2809 offers qualified credit transfers under limited conditions: group of sites that are geographically distant and exchange feedstock through either pipelines, rail, or truck; credit donor and acceptor are under the same management; the substance or product taking credit must be the same; and the use of credit transfer must demonstrate sustainability or carbon benefit as compared to physical transfer. RSB's Advanced Products standard allows credit transfers within the same certification scope and there are no geographic boundaries. RSB's conditions for this transfer include the following: both sites are covered by the scope of certification: the material is identical; measures are in place to ensure that there is no double booking; and auditors must have access to both sites and their documentation to verify that the claim is only made once.

Concerns regarding multi-site MB and the transfer of credits center around the increased complexity and communication challenge of explaining the approach to customers (e.g., buyers/distributors), consumers, brand owners, and regulators. In practice, the method may not be sufficiently traceable and, thus, may reduce credibility and threaten consumer trust in recycled content claims. Additionally, the concept of credit transfer is in effect an integration of B&C concepts into the MB system and concern arises over how to differentiate the two. In both B&C and MB multi-site credit transfers, sustainability characteristics (and associated credits) are disconnected from the physical flow of materials. *The key difference between the two is that under B&C, credits are traded and sold independently of physical materials, whereas multi-site MB credits are not sold separately from materials.* A further challenge is identifying what the appropriate geographical limits (if any) should be for managing multi-site MB. While staying within a single country may avoid issues with international laws and regulations, extending across borders or oceans may increase efficiency and more rapidly advance a circular economy in its nascent phase where the necessary volumes of recovered materials may be difficult to obtain. It is unclear how multi-site MB will be received in the US where some state and local governments are establishing minimum recycled content requirements.

2.5 Certification Requirements and Interoperability

The purpose of CoC systems, MB included, is to allow product claims to flow across supply chains and accurately reflect the sustainability characteristics of the material. Certification is always the first step in the process. Viewing the history of other certification schemes provides valuable insight into the possible trajectory of polymer recycling standard development. For example, Figure 7 provides the progression of certified crude palm oil under the RSPO strategy, displaying the certified volume (blue columns) and sold volume (orange columns) of certified material under each CoC method since 2013. The total supply of certified material has outstripped demand for many years (the opposite is true of chemically recycled polymers). It is also evident that there is a progression from 66 % B&C in 2013 (the remainder being nearly all segregated (SG)), to approximately 50 % SG + identity preserved (IP), 30 % MB, and 20 % B&C in 2020. So RSPO started with mostly B&C to get certified product into the market, which then decreased over time with a shift to mostly IP, SG, and MB, with B&C declining as more physical traceability, and higher volumes of certified supply become possible. The takeaway is that CoC models are expected to naturally progress towards more physical connection as those increased volumes are available on the market, regardless of external pressure on the standard to be more robust. MB will always play a role in commodities that are too large to have dedicated infrastructure, but IP and SG supply chains can become options as infrastructure expands and the circular polymer marketplace becomes more robust.

Key methodological considerations exist for MB certification including continuous accounting versus fixed inventory period, volume carryover and credit expiration, credit transfer, and free attribution. A continuous accounting system is one in which there is no accounting period at all, the certified volume is tracked in real-time and thus there is no ability to oversell or go negative. In some cases, an accounting period is applied. This system is less flexible but is typically easier to manage, and

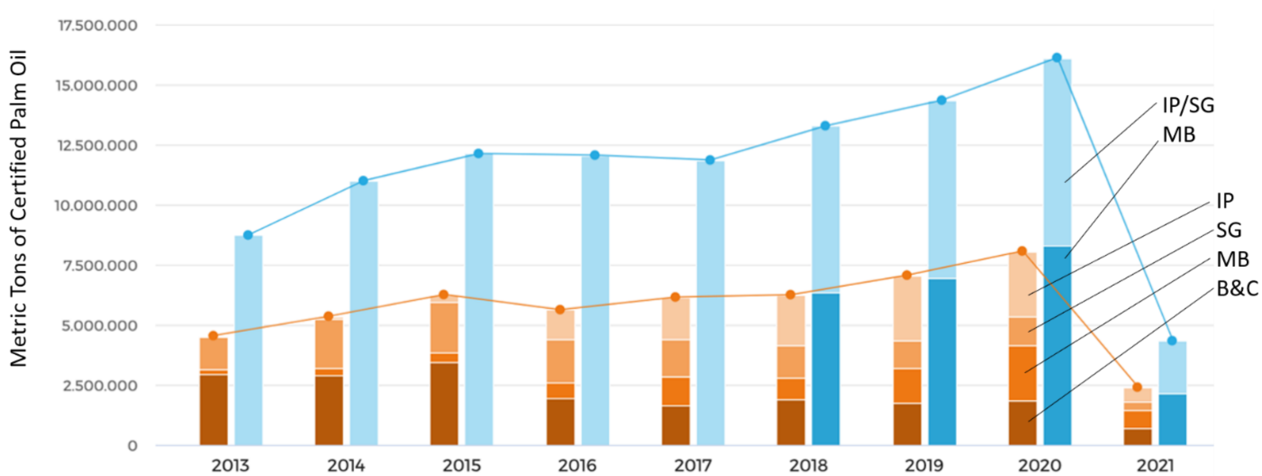

Figure 7: Progression of the RSPO scheme, representing metric tons of certified crude palm oil between 2013-early 2021. Blue columns are certified volume, orange columns are sold volume under different CoC models (IP: Identity Preserved, SG: Segregated, MB: Mass Balance, B&C: Book and Claim) [75]

thus is the most common approach used in the certification of other commodity supply chains (e.g., RSPO). Most certification tools operate on a fixed accounting system of a specified time period. The main advantage of this system is that it allows operators to “go negative,” or overdraw (oversell) certified material within an accounting period. While operating on defined time intervals, some certification systems allow forwarding of positive credits from one MB period to the next as long as there is a valid certificate. It is of note that the continuous accounting system is the preferred method for the majority of RSPO Supply Chain certified actors (e.g., downstream food processors such as bakeries and chocolatiers), likely due to its simplicity and because they are often trying to meet the demand for a specific customer as opposed to managing their MB system to their own greatest benefit. This could be the case in the polymers industry as well, where the current focus is often upstream (e.g., resin producers) but the real volume in the sector is downstream (e.g., injection and blow molders, etc. - those who use the resin).

Another key methodological consideration is volume carryover and credit expiration. Most MB schemes allow for a carryover from one period to the next, however some have certain restrictions. An operator can “bank credits” until prices are favorable, creating a speculative market. Alternatively, an operator may “bank credits” in order to allow a value chain partner to obtain certification, to accommodate challenges in securing steady supply of waste plastic feedstocks or to acquire critical mass of a certified product. In practice, MB-certified products are more expensive, making banking indefinitely unlikely. Some schemes have an expiration on credits. For example, RSPO claims must be made within 12 months of the date of credit purchase. Discrepancy arises in stakeholder discussions about volume carryover limitations and credit transfer allowances.

A final methodological consideration is that of Free Attribution associated with multiple outputs as well as inputs. Many chemical recycling systems have multiple outputs, such as from a steam cracker, and Free Attribution allows for all sustainability claims to be assigned to any one of the outputs. However, many systems also have multiple inputs, which makes MB more complicated. Both RSB and ISCC Plus allow for one feedstock to be overrepresented in one product stream at the expense of the others. While ISCC recommends against this, if it is performed, it must be made transparent to customers and is normally done on an energetic basis. RSB requires a normalization based on fossil fuel consumption to make a fossil fuel substitution claim.

2.6 Regulatory Landscape

The United States has implemented limited statutory or regulatory drivers for plastics recycling in general and MB specifically. The U.S. Food and Drug Administration (FDA) approves the use of post-consumer recycled resin (PCR) in food contact use on a case-by-case basis. The Federal Trade Commission (FTC) publishes the FTC Green Guides to help marketers avoid making environmental marketing claims that are unfair or mislead consumers [76]. To date, the Green Guides have not included guidance related to MB recycled content claims, although this topic may be discussed when the Green Guides undergo review in 2022. The U.S. Environmental Protection Agency (EPA) has established a goal of reaching a national recycling rate of 50 % by 2030 by strengthening economic markets for recycled material, making domestic recycling infrastructure more efficient, and reducing contamination in recycling. Many stakeholders submitted comments on whether to include chemical recycling in the scope of the National Recycling Strategy. In response, EPA authors stated that all options, including chemical recycling should be discussed when considering methods for sustainably managing materials. Therefore, chemical recycling is part of the scope of this strategy and further discussion is welcome. [77, p. 6].

The EU has taken stronger measures to promote and advance plastics recycling (e.g., [51, 52, 72]), and chemical recycling is viewed as a promising technology in that effort. As part of the implementation of the Single Use Plastics Directive [72], the European Commission has committed to develop a method for calculating and verifying recycled content by January 1, 2022 [78].

Additionally, an amendment to the food-contact recycled plastics regulation (EC No 282/2009 [79]) is in development. Further, emerging European plastic taxes, such as the tax of €0.80 (about $1.00) per kilogram on non-recycled plastic packaging waste effective Jan.1, 2021 [80], will increase incentives for recycled plastics and boost recycling rates.

The new ISO Technical Committee (ISO/TC308 *Chain of custody*) is working on separate standards for MB and B&C that will, if implemented, ultimately facilitate harmonization in terminology and approaches, which currently differ across the available CoC certifications. Recycled content certifiers have indicated that they will align their certifications in accordance with the forthcoming ISO standard.

Due to the European initiatives on plastics recycling, most MB systems certifying circular polymers were developed for the European market and are operated by EU-based entities. ISCC Plus and RSB, based in Germany and Switzerland, respectively, have a significant market influence, which could serve as a potential barrier for acceptance in the U.S. considering the substantially different business and regulatory environment in the U.S. Additionally, U.S. states are proposing recycled content mandates without including chemical recycling and MB measures (e.g., [4], [5], [6], and [7]). This could result in a patchwork regulatory system in the U.S. complicating recycling and the use of MB accounting. Further, there is currently no alignment around key components of an MB framework in the U.S.

2.7 Brand and Consumer Awareness

Chemical recycling is intriguing for brands due to the increased quantity and quality of recycled resins that need to meet various higher requirements (e.g., food and medical grade, color, performance, etc.). While physical segregation of recycled resins would be preferred by brands, this is not currently possible. Therefore, a creditable and transparent MB system is crucial to meet demand and will require brand acceptance. Concern was expressed at the workshop that misuse and/or misunderstanding of the MB system could significantly undermine credibility of claims, and thus, trusted and understandable standards are critical to allow brands to account for both aggregate reporting (e.g., corporate average) and on-pack recycled content claims.

The Consumer Goods Forum (CGF) is an organization that brings together CEOs from consumer goods manufacturers and retailers globally to collaborate on initiatives that aim to secure consumer trust and drive positive change [81]. Current coalitions include environmental and social sustainability, health and wellness, food safety, and product data accuracy. The CGF has taken an interest in chemical recycling and MB and is currently developing an internal position paper. Brands are also closely following position papers published by other organizations and industry groups (e.g., [82], [83], [84]).

A key message from the workshop was that on-package communication is important from a brand owner perspective and this requires clear definitions and authenticity to guarantee that the recycled polymer originating from chemical recycling can be credibly claimed on the label. Certification plays an important role in the clarity and credibility of claim information. Increased transparency is essential, particularly information sharing between resin producers and brand owners where quality of information is more important than quantity. Claimable credits must be understandable and agreed upon, and the transfer of credits must be traceable. As such, brands called for uniform standards that the whole industry can use, and consumers can understand (or at least accept). For example, stating specific, certified levels of recycled content on a given package was considered positive, without any need to go beyond into details of fractions from specific recycling pathways. Corporate averages were also proposed as a strategy to market recycled content, though more work would need to be done to ensure consistency and agreement among stakeholders. Fundamental to on-package communication is that it supports consumer buy-in, as this is critical to drive market development for recycled materials.

To address many of the needs mentioned above, and due to the future needs of industry to expand the use of these and similar tools, there is a need for training and education efforts. For example, The Recycling Partnership has an ambitious five-year vision to improve the recycling system overall. [85] They estimate that action would create almost 200,000 jobs, which would depend on working knowledge of advanced infrastructure with updated technology, in addition to a better informed consumer who can trust the system and who feels invested and included in its success. The need applies to both technical experts in science, engineering, and economics, as well as other stakeholders in a more circularly-integrated economy. This will require collaboration with academia, and resources ranging from use-case data to new models and decision-making supporting tools to accessible language in adjacent fields. The effort required is sufficiently divergent from traditional approaches in both complexity and scale, such that new, ambitious, public-private partnership models will likely be necessary to enable progress.

3 Findings

Several key findings were brought to light through workshop presentations and discussions. MB accounting is a key enabler to accelerating the adoption of chemical recycling technology. The supply of recycled plastics cannot yet support the development of dedicated chemical recycling infrastructure. Chemical recycling, as a complement to mechanical recycling, has the potential to increase recycled polymer availability and quality that is necessary to meet brand recycled content commitments. Support for implementation of MB certification transcended most different types of participants in the workshop. However, the application of these tools to the complex polymer manufacturing industry (e.g., varying chemical processes and scales and a complex supply chain) is in early stages and there are many unsettled issues, ill-defined terms, and conflicting objectives.

MB accounting is not a new concept, but rather has a long history in select sectors and is only newly being applied to the manufacture of polymers. It is best suited for nascent industries when feedstock, technology, or infrastructure is not sufficient to support segregated or identity preserved CoC models. As such, MB supports the cost-efficient scale-up of sustainable materials by mixing those materials with conventional feedstock and integrating them into existing supply chains, processes, and infrastructure.

Clear goals and objectives are necessary in the development of an MB certification system to align system components accordingly and ensure support and buy-in from stakeholders throughout the value chain, including regulatory agencies (e.g., FTC), consumers, the plastics supply chain, recyclers, and NGOs. Potential objectives for an MB system certifying circular polymers include (1) displacement of fossil feedstocks, (2) maximum diversion of waste plastic, (3) retention of materials (and molecules, e.g., energy byproducts such as CO_2) within the circular economy, and (4) recycled goods with virgin-matched properties, as quickly as possible to accelerate the transition to a more circular economy. Each of these will affect the formalisms, prioritization, and decision making differently in an MB standard and will influence choices such as accounting for fuels, establishing credit systems, and allowing site transfers.

Using common, well-defined approaches to set boundary conditions is critical to determine the applicability of the MB system and establish its scope. Principles must be developed around input and output connectivity, process scope (e.g., unit, site, or multi-site level), geographic boundary (systems operating within one country, across a single border, or internationally), and temporal conditions (i.e., balancing period). System boundaries should also be specified for large global organizations with multiple legal entities. Boundary conditions need to be clearly defined and transparent to address the lack of NGO confidence and potential lack of consumer confidence.

Interoperability of MB tools and data frameworks across standards and certification systems is important for integrity and transparency. It is also necessary for the inclusion and accountability of all players in the supply chain (e.g., upstream processors as well as downstream converters such as blow molders). Interoperability requires aligning on certain definitions and terminology followed by aligning on methods (e.g., credit allocation).

Legal and regulatory barriers to MB in the U.S. center around the current variability at state and local levels regarding plastic waste management and recycling. Further, some states are proposing recycled content mandates without chemical recycling or the inclusion of MB accounting, while others are proposing laws that advantage or promote chemical recycling [86, 87, 88]. The disparate nature of state and local initiatives and exclusion of chemical recycling and MB ultimately hinders the broad scale-up and distribution of manufacturing and may enhance the desire for multi-site credit transfers artificially. As a result, an opportunity for well-conceived national policy could expand technology and feedstocks, increase recycling, increase consumer confidence in approaches under development, and provide industry with a more predictable legal and regulatory landscape to justify more investment and financial risk taking. Additionally, there is currently no alignment around key components of an MB framework in the U.S. Future policy approaches could dramatically affect implantation strategies and technology adoption. For example, minimum recycled content requirements could specify volumes and feedstock sources, which would drive the development of chemical recycling in conjunction with mechanical recycling to meet recycling and circular economy goals.

Much of the discussion around and development of MB methods involves the life cycle assessment (LCA) of circular polymers. LCA is a scientific approach that quantifies the environmental impacts of products across their life cycle including extraction of raw materials, manufacturing, transportation, consumption, and disposal [89]. LCA has been applied to a broad range of plastic materials and products, but the ability to evaluate the wide range of existing and potential polymers is still limited, including a lack of reliable data. The assumptions in an LCA influence the relative performance of plastic feedstock options (e.g., bio-based vs. fossil fuel-based), plastic packaging and product design (e.g., degradable vs. recyclable), as well as how we prioritize recycling processes (e.g., mechanical vs. chemical). Again, this is affected by the overarching goals and the boundary conditions laid out in the framework of the MB system. Many unknowns remain in this space, and more research is critical to solving problems and improving systems. Furthermore, any comprehensive assessment of the circularity of various polymers or their climate impacts will require significant advances in the tools and data currently available to evaluate the entire economic, manufacturing (including design and technology), social, and environmental landscape. This will also require complementary advances in technoeconomic analysis tools to evaluate the full performance landscape and tradeoffs associated with different approaches to solving the problem. It is NIST’s opinion that such information is not currently available and is a major opportunity for a coordinated research and development effort. While there is some early progress in this area, significantly more investment is needed.

Still, a credible and transparent MB system is crucial to establishing a business case to expand the circular economy and support movement of materials through the full supply chain. Messaging and understanding of the specific claims arising from MB certifications, both business-to-business and to the consumer, is a challenge. MB systems have largely been developed from schemes that were not consumer facing (even in cases where consumer-facing labels may have resulted, e.g., FSC and Fair Trade), and we are still learning how consumers will react to MB for chemical recycling. Consumer, or at least brand, understanding and trust in the MB system is important to drive market pull for recycled content because it is clear that consumer-facing labels can affect consumer behavior and the reputability of brands and products which use those labels. Yet, the minutiae of MB accounting systems, while important to ensure credibility, may be too complex for most consumers and perhaps even some brand owners to fully understand. This presents some risk to the brand owner, who does not want to be vulnerable to accusations of misleading claims or misrepresenting their products' origins, even when those accusations may be due to misinformation, misunderstanding, or other communication challenges.

There is a certain amount of flexibility needed in MB accounting to drive scale and immediacy of recycling operations and to not load the system with added cost that would be a fundamental barrier. However, flexibility must be balanced with the right level of credibility (as ensured through third-party audits/certification) to ensure support from brands, consumers, and NGOs. The most credible system is that closest to traditional "accounting".

Additionally, there is a need for education of a future workforce in support of the practice and management of plastics in a circular economy. Data collection, management, and processing are increasingly necessary in recycling and manufacturing and are essential to MB accounting. Circular economy principles, chemical and mechanical recycling practices and challenges, and data science should be integrated into curriculum design and training programs.

A final finding is that the general perception of MB accounting for polymers is that it is a necessary but complex tool that will help expand plastics recycling. For example, Figure 8 provides the word-cloud poll results collected by workshop participants when asked how they would describe MB accounting for polymers. Immediate action is needed to address the conflating challenges of the current linear economy for polymers and accelerate progress in reducing the negative impacts of the current system. Any early implementation is likely to involve challenges; reevaluation and progressive improvements should be expected in any system.

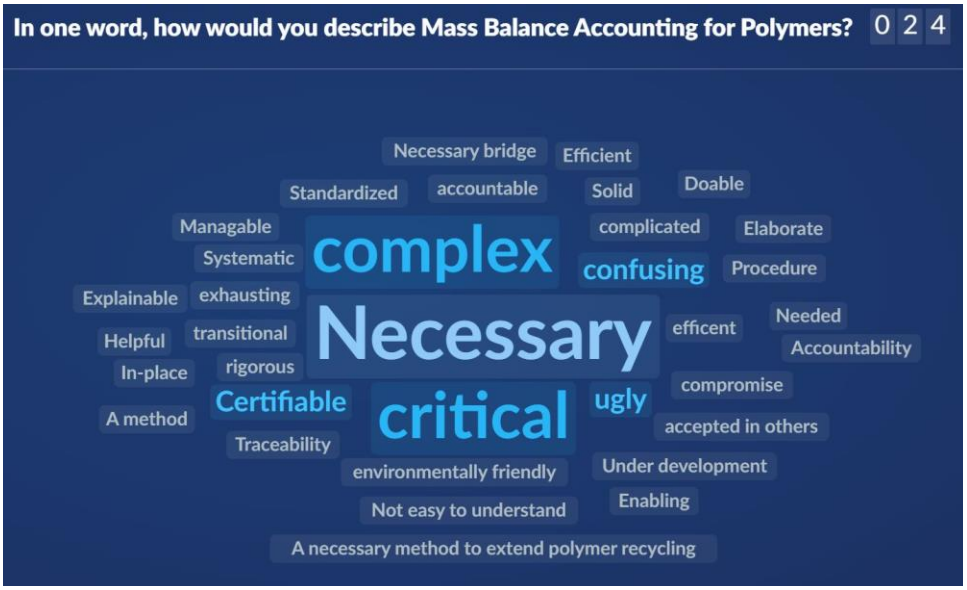

Figure 8: Workshop participants' word-cloud response to poll question asking for one-word description of mass balance accounting for polymers

4 Recommendations

Based on the workshop findings, NIST has the following recommendations for the advancement of MB accounting for circular polymers:

1) Establish clear, prioritized technological, environmental, social, and economic goals for transitioning towards a more circular economy for polymers (e.g., diversion of plastic from waste and pollution streams vs. improving environmental impact of the industry/modern society vs. displacing virgin feedstocks) in which the desired results are measurable and the data publicly available. Otherwise, any approach is vulnerable to confusion and miscommunication across the supply chain in the best case, and claims/accusations of malfeasance or greenwashing in the worst case.

2) Adopt a national strategy for the implementation of rigorous MB accounting methods for circular polymers to rapidly expand capacity and markets for recovered polymers, particularly in products which are difficult to reuse or recycle by other means. The strategy should be aligned with achieving the prioritized goals in recommendation 1, directly address controversies, particularly the inclusion or exclusion of fuels and energy losses, and may include a phased approach.

3) Establish processes and frameworks that promote successful expansion of capacity and markets for both mechanically and chemically recycled polymers. Do not set them up to compete with one another for the same easily accessible feedstocks. A first step could be to improve post-consumer collection, segregation, and isolation nationally to increase available feedstocks.

4) Develop open, consensus-based standards for certification methods and tools that are transparent, interoperable or reciprocal, and available to the entire supply chain. Multiple competing platforms, or expensive training and certification qualifications will disadvantage small and medium business, many of whom operate between the large, global businesses currently at both ends of the linear economy.

5) Establish transparent, auditable data, data standards, and a framework suited to the needs and integrity of the entire supply chain.

6) Align definitions, terms, and methods necessary for standard's harmonization, interoperability, and broad adoption. Further, mutual recognition is necessary for interoperability across standards, which is possible with appropriate benchmarking to ensure schemes have equal integrity, security, and verification methodologies.

7) Invest in a multidisciplinary research and development program at the interface of polymer science and engineering, manufacturing, economics, and data (privacy, sharing, and access) to enable manufacturing innovation, stronger decision making, improved education and communication tools, and improve supply chain integrity and accountability for circular polymers.

Accurate assessment of the full environmental impacts of circular polymers depends on more and better data from all these disciplines and strong partnerships between the private sector, educators, and government.

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Appendix A: Agenda

Time (ET)	Monday, May 3	Tuesday, May 4	Wednesday, May 5
10:00	Plenary 1: Plastics recycling and the role of mass balance accounting; Andreas Kircherer, BASF	Plenary 2: Panel of Standards Bodies; ISCC, RSB, UL, GreenBlue, FSC	Plenary 3: EPA's National Recycling Strategy; Kim Cochran, US EPA
10:15			
10:30			
10:45	Session 1: Definitions	Session 3: Multi-Site Claims/Credit Transfers	Session 5: Legal & Regulatory Barriers/Support
11:00			
11:15	Breakout Discussion	Breakout Discussion	Breakout Discussion
11:30			
11:45			
12:00	Lunch	Lunch	Lunch
12:15			
12:30	Session 2: Allocation	Session 4: Certification Requirements & Interoperability	Session 6: Consumer Awareness
12:45			
1:00	Breakout Discussion	Breakout Discussion	Breakout Discussion
1:15			
1:30			
1:45	Closing Remarks	Closing Remarks	Closing Remarks

Appendix B. Workshop Speakers and Participants

Speakers

Name	Affiliation	Session
Andreas Kicherer	BASF	Plenary 1
Elena Schmidt	RSB	Plenary 2 (Panel)
Jan Henke	ISCC	Plenary 2 (Panel)
Bill Hoffman	UL	Plenary 2 (Panel)
Laura Thompson	GreenBlue	Plenary 2 (Panel)
Emily Crumley	FSC	Plenary 2 (Panel)
Kim Cochran	US EPA	Plenary 3
Bill Hoffman	UL	Session 1: Definitions
Laura Thompson	GreenBlue	Session 2: Allocation
Jason Pierce	Eastman	Session 3: Multi-site claims/Credit transfers
Matt Rudolf	SCS Global Services	Session 4: Certification requirements/interoperability
Steve Alexander	APR	Session 5: Legal & Regulatory Barriers
Craig Cookson	ACC	Session 5: Legal & Regulatory Barriers
Jun Wang	Colgate-Palmolive	Session 6: Consumer awareness

Participants

Name	Affiliation
Ron Abbott	Chevron Phillips Chemical Company
Holli Alexander	Eastman Chemical Company
Stephen Alexander	Association of Plastics Recyclers
Bob Armantrout	SCS Global Services
Gibson Batch	3M
Julie Beaudry	FLEXcon
Kathryn Beers	National Institute of Standards and Technology
Roy Bertola	LanzaTech
Stephen Borg	The Keelen Group
Melanie Bower	ExxonMobil
Cassie Bradley	INEOS Styrolution
Aaron Burkey	National Institute of Standards and Technology
Nina Butler	Stina Inc
Edith Cecchini	Ocean Conservancy
Madhusudan Chari	3M
Benjamin Chen	Mattel
Stan Chen	RecycleGO, Inc.
Kim Cochran	US Environmental Protection Agency
John Cook	Niagara Bottling, LLC
Craig Cookson	American Chemistry Council

James Coomes	Pepsico
Emily Crumley	Forest Stewardship Council (US)
Michael Dabbene	ERG Energy Efficiency
Shalto Dascher	Niagara Bottling, LLC
Kate Davenport	Eureka Recycling
Paul Donovan	Americas Styrenics LLC
Cynthia Ebner	Sealed Air Corporation
Sarah Edwards	Eunomia Research and Consulting
Salvador Escobedo-Salas	University of Western Ontario
Rebe Feraldi	LAC Group
Amanda Forster	National Institute of Standards and Technology
Diana Hajali	International Trade Administration
Caitlin Harrington-Smith	Eunomia Research and Consulting
Jan Henke	ISCC
William Hoffman	UL Environment
Kim Holmes	4R Sustainability
Mark Horley	Greenback Recycling Technologies
Derek Huang	National Institute of Standards and Technology
Andreas Kicherer	BASF
Joshua Kneifel	National Institute of Standards and Technology
Rajendra Krishnaswamy	Braskem
Jill Lawton	Total Petrochemicals & Refining USA
Tiana Lightfoot-Svendsen	U.S. Plastics Pact
Eric Lin	National Institute of Standards and Technology
Paula Luu	Closed Loop Partners
Matthew Marks	SABIC
Tyler Martin	National Institute of Standards and Technology
Margaret McCauley	US Environmental Protection Agency
Thomas McKay	BASF Corporation
David Meyer	US Environmental Protection Agency
Kalman Migler	National Institute of Standards and Technology
Shannon Milburn	ExxonMobil
KC Morris	National Institute of Standards and Technology
Mendy Mossbrook	Sealed Air Corporation
Prapti Muhuri	American Chemistry Council
Bruce Murray	Chevron Phillips Chemical Company
Wilhelm Myrer	Empower
Ganesh Nagarajan	LyondellBasell
Carl Nesset	Empower
Ihab Odeh	SABIC
Diego Orozco	Mibanco
Sara Orski	National Institute of Standards and Technology
Carrie Pearson	3M

Jason Pierce	Eastman Chemical Company
Christina Progess	US Environmental Protection Agency
Matthew Realff	Georgia Tech
Maya Reslan	National Institute of Standards and Technology
Kiran Rezvani	Ameircas Styrenics
Rachelle Riegerix	US Environmental Protection Agency
Elizabeth Ritch	GreenBlue
Matthew Rudolf	SCS Global Services
Elena Schmidt	Roundtable on Sustainable Biomaterials
Kelsea Schumacher	National Institute of Standards and Technology
Charlie Schwarze	Keurig Dr Pepper
Bianca Shemper	Solvay Specialty Polymers, L.L.C.
Yoan Simon	The University of Southern Mississippi
Nicole Smith	Ernst & Young
Raymond Smith	US Environmental Protection Agency
Miriam Swaffer	SCS Global Services
Christopher Szakal	National Institute of Standards and Technology
Ryan Tappel	LanzaTech
Laura Thompson	GreenBlue
Jon Timbers	Americas Styrenics LLC
Jozef Van Kerrebrouck	Berry Global, Inc.
Lauren Versagli	Plastic Energy
Jun Wang	Colgate Palmolive
Gary Welsh	Americas Styrenics LLC
Francisco Zubeldia	Brightmark

Appendix C. General and Unaddressed Comments on Report from Workshop Participants

General Comments
“Excellent paper factual and pedagogic, the best I have seen so far on this complex and sensitive topic.”
“Appreciate the extensive effort invested by NIST in organizing and conducting the MB workshop followed by summarizing in a report. The report is very thoughtfully conceived and well organized.”
“The report provided a good reference for the current status of plastics recycling in the US, the challenges surrounding the use of mass balance accounting, and the recommendations for spreading this approach to advance circularity in the chemical industry.”
“As there is significant momentum at the state and national level around recycled content mandates, there is such a need for further conversation about the role of Mass Balance and credit trading. You highlight the need to look at MB and credit trading potentially through the lens of a scale down method as more supply becomes available. This seems extremely important.”
“Need to separate "fuels" from chemical recycling. For plastic circularity, this is generally not an accepted use of chem cycled output with mass balance. Need to state this clearly in this document.”
“Mass balance principles are a crucial bridge for the plastics industry as it transitions towards upscaling of production using alternative feed stocks.”
“The problem of the plastics economy is that it is too successful. Those who bash plastics offer no comparable material solution to human needs that is ‘better’ overall. NIST should recognize that plastics are not evil nor the scourge of the planet, but a useful family of materials that modern life needs and should be nurtured.”
“[NIST should…] Frame Mass Balance as Commonly Utilized: The report and Congressional mandated study should more clearly state that mass balance is not a new concept, but an accepted and certified bookkeeping method that has been successfully used in other commodity sectors for decades and is trusted by both regulators and consumers.”
“[NIST should…] Create More Urgency for Implementing Mass Balance. Aggressive goals on the use of recycled plastics/content in plastics packaging and other products have been established by many companies across the plastics value chain. States are also moving ahead in mandating recycled content and the U.S. EPA committed to increasing the national recycle rate to 50 percent by 2030. In order to meet these ambitious goals, there should be more urgency with governmental bodies and private industry to establish mass balance standards and promote industry and consumer acceptance.”
“[NIST should] Play a Constructive Role in the Fuels Discussion. The draft Report references fuels were a source of controversy. While there is not yet consensus on the allocation rules for fuels, there is an opportunity to develop a policy framework that is best suited to the U.S and North American recycling systems.”

Unaddressed Comments	
Location/Reviewer Comment	**Response**
Executive Summary Comment: The conclusion that mechanical recycling infrastructure alone cannot supply need and demands needs more data and back up. There is a lot of debate within the recycling industry about the viability and environmental impact of chemical recycling. There is need for increased investment in mechanical recycling and there needs to be accountability to make sure that chemical recycling doesn't become a shiny object that distracts that investment in mechanical recycling when chemical recycling really hasn't proven out at a commercial scale. You address this debate in other parts of the paper, which I appreciate, but I think it needs to be said upfront.	Yes, it was clear from the workshop that there is a need for more investment and innovation in mechanical recycling infrastructure and technology. It is not clear what fraction of the total plastic flow can be accommodated by an expanded and advanced mechanical recycling sector, but it should be supported robustly. The report makes clear that one pathway's needs should not distract from the other and they both need to grow and be supported in order to rapidly change the way plastic and many polymeric materials move and recirculate through the economy. We felt this was adequately reflected in both the summary and the report.
Executive Summary/Key Findings Comment: I don't agree there are conflicting objectives - we all want to see three objectives met: 1) difficult to recycle plastics recovered 2) fossil feedstock displaced by recycled feedstock 3) decreased carbon usage Uniform mass balance principles are needed to accomplish these tasks. But in applying MB accounting, specifics surrounding implementation of these principles must be tailored to the polymers industry with provisions that meet the needs of ALL stakeholders across the value chain.	The determination of overarching goals was not part of the workshop objectives and would require substantially more engagement with stakeholders. We did not assess in the workshop whether everyone would consider reduced fossil feedstock usage and decreased carbon usage as common goals. However, it was clear from the workshop discussions that not all participants were only considering 'difficult to recycle plastics', nor that there was agreed upon definition of what 'difficult' means in this case. For some, clearly reducing plastic pollution in the environment is the primary goal. This is why we recommend more explicit consideration of both pollution and climate factors in determining common objectives.

Executive Summary/Key Findings <u>Comment:</u> The focus should be on mass balance chain of custody requirements. Other sustainability topics, such as CO2 impact and other life cycle assessment impact areas, should be left to other legislated or voluntary programs. Section 3, discussion of LCA of circular polymers <u>Comment (following statement of insufficient data to determine circularity of polymers…):</u> …but shouldn't be part of recycled content accounting methods. Again focus on the topic at hand and don't integrate too many variables which, in the case of GWP from an LCA, can be misleading.	Due to the conflicting objectives stated and implied throughout the report, and as supported in the workshop discussions, the goals of more circular polymer products are intimately intertwined with both pollution and climate impact minimization. Therefore, the relationship between pathways through the circular economy, and overall negative impacts cannot be decoupled from mass balance methods, particularly where there is subjectivity in the relative priorities of how those assessments are determined which directly impacts tradeoffs between those two key issues.
Executive Summary/Key Findings <u>Comment:</u> Although this addresses differences in certification body requirements, I don't think it does so strong enough. These differences in requirements for certification, some with monopolistic intent, are a hinderance. Need a simple, mass balance allocation method without ancillary topics and with certification reciprocity to each other so the supply chain can operate efficiently	We felt we had captured these issues as well as possible without over-representing the outputs of the workshop discussions. We had no evidence from the workshop output to justify any judgements of any monopolistic intents that may or may not exist within some certifying third parties.
Section 1.2, paragraph 3 <u>Comment:</u> Chemical recycling would require facilities for pyrolysis, for example. But mechanical recycling would also require sorting/ cleaning/ breakdown facilities, and the CAPEX might be lower for those facilities? How would CAPEX compare?	The CAPEX comparisons between chemical and mechanical recycling facilities is unknown and is beyond the scope of this report. The referenced paragraph only conveys that chemical recycling processes have the potential to utilize existing infrastructure and therefore may not require the construction of new facilities. However, there is debate amongst the industry about whether chemical recycling will require significantly more capital investment. Additionally, it is yet unknown how much sorting infrastructure will be needed for feedstocks for chemical recycling. The potential relative investments in these areas to support maximizing all recycling pathways should be assessed.

Section 2 Overview <u>Comment:</u> The CRITERIA for defining MB principles are in place with internationally recognized systems, but are being brought into question by some parties. Since these are voluntary systems, customers are able to accept or reject these approaches. The market and regulators must determine the most suitable approaches.	We hope this report can help to inform how regulators and/or market influencers might approach the task of determining suitable approaches.
Table 1 <u>Comment:</u> The standards summary table (table 1) offers an overview of the types of materials and industries certified, but in general does not describe the differences between the standards. Suggest adding distinguishing factors, such as general boundary conditions for the mass balance systems (e.g., physical connection required, multi-site transfer within a company / geography, etc.)	We sought to capture key differences in the text of this section because we felt it was too difficult to simplify down without making the table overly complex and difficult to read.
Section 2.2, Post-Consumer vs Post-industrial Bullet point, re: “100% of credits”. <u>Comment:</u> Adjusted for manufacturing losses (ie, credits can only be applied to usable or salable products)	There is debate over how to address credits and how to apply them to products accounting for losses, a well as how to best represent them to the customer/consumer.
Section 2.3, Paragraph 2 <u>Comment:</u> “standards established by MB approaches must be clearly articulated - they are already defined” Recommendation #4 <u>Comment:</u> I do not agree that more standards is a desired outcome. Rather, harmonization of existing standards that already handle chemically recycled materials would make more sense, given that these standards have developed requirements to specifically handle some of the challenges and sustainability risks associated with this feedstock, and given all of	There appears to be misunderstanding between ‘certifications’ and ‘standards’ among the community. Per ISO definition, standards are documented agreements set through consensus from the full community containing technical specifications or other precise criteria to be used consistently as rules, guidelines, or definitions. Certifications are procedures by which a third party gives written assurance that a product, process, or service is in conformity with certain standards or predetermined specifications or definitions. As such, certification is a form of communicating along the supply chain which may or may not conform to formal standards. Policies involve both the interpretation of standards and the ability/inability of certification platforms to meet given standards. Policies can

the learnings that these existing standards can apply having rolled out certification already in a chemical recycling context.	also set expectations for what is delivered by both standards and certifications.
Section 2.3 <u>Comment:</u> Consider adding commentary to point out that there are many chemical recycling processes (both commercialized and in development) where there are no losses to fuels - or where the only losses are fuels consumed by the process itself. I.e. This issue applies primarily to certain technology pathways that generate and sell fuels.	This comment is duly noted, but was not a point discussed more broadly in the workshop. It also delved into details of future technology and plans that we did not have direct access to assess.
Section 2.3 <u>Comment:</u> Note that mandatory GHG emission reductions for 'circular fuels' may well also naturally reduce the competitiveness of using chemically-recycled plastics as a feedstock for fuels. Fuels are required to meet certain emission reduction targets in order to be certified. If their combustion results in the release of fossil-plastic-origin GHGs into the atmosphere, then the overall GHG emission reduction created by these fuels is likely not to be great enough for them to be certified anyway - thus chemically-recycled feedstocks will only make sense for use in non-energy markets	This is a very interesting and related comment, but it was not a part of the discussions captured from the workshop, and it was not clear where it could be incorporated into the report in a manner that would properly reflect input of all the workshop participants.
Section 2.4 <u>Comment:</u> Are QCT's for same products only?	Yes, there is confusion about whether or not Qualifying Credit Transfers (QCTs) should be limited to transfers between sites manufacturing the same products or not, but this was beyond the scope of discussion in the workshop. It would certainly need to be worked out in any documentary standards seeking to unify practices of various assessment tools.
Section 3 <u>Comment:</u> NIST needs to use examples to teach about what Mass Balance is and is not	We felt that there were good examples of many limitations and benefits to Mass Balance from the workshop recordings, which for length of this report, we chose not to include. We also felt that there were multiple references within Section 2 describing its benefits and limitations.

Section 3 <u>Comment:</u> market forces will ultimately determine what approaches are the most effective, both technically and financially.	One thing that was very clear from the workshop is that there are strong opinions about whether or not market forces can be left in isolation to determine most effective approaches with the most beneficial outcomes for all stakeholders.
Recommendations <u>Comment:</u> Consider adding a timeline to achieve the goal of implementing the recommendations	We would love to see a clear timeline proposed for progress on this topic, however, it was beyond the scope of the workshop, and beyond the scope of NIST's associated responsibilities to propose a timeline in isolation from consideration of other agencies and stakeholders in the process.
Recommendation #2 <u>Comment:</u> …regarding CO2 footprint: It seems that the same attributes that make a PCR bale good for mechanical recycling make it good for chemical as the chemical process don't seem to be a flexible as they are being touted. While reducing waste is a great goal, we need to also reduce carbon	Yes, this is an excellent comment, and one we hope was captured in multiple locations in the report. This is why the overarching goals need to be prioritized in order to inform what kind of constraints and incentives should be placed on the system.
Recommendation #3 <u>Comment:</u> I'd like to understand more about this statement (e.g., in what scenarios this could happen & how to prevent). My first thought was that they would not compete for feedstocks, but that may not be true. Consider eliminating the second sentence. Market dynamics and pricing will ensure chemical and mechanical recycling do not compete for the "same easily accessible feedstocks." We do not see a need for a framework to prevent competition for materials.	Yes, we agree that more information is needed here, but it was also clear from the workshop that this is a major concern for multiple parties. Even from the groupings of these two comments on the same recommendation it is clear that different stakeholders are looking at this problem very differently. It did seem clear from descriptions of some chemical processes that they were interested in the same high quality sorted bales, whose short supply are currently holding back growth in the mechanical recycling market.