7th European Conference on Industrial Engineering and Operations Management
Augsburg, Germany, July 16-18, 2024
Publisher: IEOM Society International, USA DOI: 10.46254/EU07.20240201
Published: July 16, 2024

Uncertain Supply of Recycled Plastic: Challenges and Mitigation Strategies for Adopting Plastic Circular Economy

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Abstract

Plastic waste is one of the major constituents of environmental pollution due to the increasing applications of plastic material in today's economy. Regulation and customer preferences compelled firms to use recycled plastic (RP) for sustainable production and a circular economy. Companies have already started using recycled plastic from the market in the open-loop supply chain system, but they are facing issues in managing that with the current planning system due to unpredictable variations in quality, quantity, lead time, and prices. As a result, their production system is affected by shortages, increasing waste, high maintenance costs, and poor product quality, which ultimately results in high cost and customer loss for circular businesses. This paper first identifies the sources of these variations in the supply of RP to guide industrial experts and practitioners to avoid when transforming businesses from linear to circular systems. Ineffective recycling processes, inexperienced recyclers, competition against incineration, and a poor supply market are the main problems that make the supply chain more vulnerable. Secondly, a strategic framework is developed based on infrastructure design, technology, production planning, product design, supplier integration, and customer engagement to guide firms in making their production system and supply chain resilient against the uncertain supply of RP in closed-loop supply chain management.

Keywords
Closed-loop supply chain, recycled plastic, circular economy, supply-oriented variations, and production decisions.

1. Introduction
Plastic is a wonderful material due to its properties of being light lightweight, durable, and highly flexible, and has a wide range of applications in the automotive, electric, and electronic equipment, and packaging industry (Xometry 2023). However, due to its polymer properties, long-lasting degradation in air, and insoluble properties, plastic waste is producing severe damage to the environment i.e., carbon emissions, landfills, and marine pollution. It is estimated that 65% of plastic waste is still not valorized into the circularity and the recycling rate is around 13% higher when they are collected separately as compared to mixed collection schemes in Europe (Europe 2022). European Union 2050 target for achieving a circular economy considers plastic as a priority dimension to control (Yalçın et al. 2024). European Union is regulating the plastic industries to use circular plastic at least ten percent (10%) in the process and expects to increase the composition up to thirty percent (30%) in 2030 to achieve sustainability goals (Watkins and Schweitzer 2018). A treaty was called by the MacArthur Foundation regarding plastic ending up 40% in the environment including packaging, and as a result, a resolution was passed in 2022 by the UN Environmental Agency to legally binding rules on plastic pollution through a comprehensive circular economy (Ellen-MacArthur-Foundation 2022).

Firms have also started working on research and development of efficiently utilizing recycled plastic (RP), and many small suppliers have also modified their processes to recycle plastic material from waste collectors. In Europe, it is estimated that RP used in the packaging has increased by 43% since 2018 (Europe 2022). However, due to less experience, unknown sources of material, lack of technology, ineffective sorting, and inadequate recycling processes,

the RP supply market is underdeveloped. Firms have started using recycled plastics (RP) as raw material due to government regulations and eco-friendly customers; however, they are compelled to take the RP from the market with uncertain quantity, quality, and lead time. These variations in the supply of RP produce a ripple effect in the whole production system (Dolgui et al. 2018). The supply chain transformation is required to neutralize the variations in raw materials and resulting uncertainties due to the addition of recycled plastic from the supplier side for resilience in supply chain management. To manage these variations, firms should modify their supply chain from an open loop to a closed-loop system, where they are showing socially responsible production by taking back their products from the customers, cleaning, and recycling them with their integrated/ collaborated recycles. The level of variations is relatively low where there is controlled lead time, quantity, and quality of recycled material. However, in a closed-loop supply chain, firms need to develop a takeback infrastructure, supplier collaboration, product design, production planning, data management, and customer engagement to successfully transform the linear economy of plastics into a circular economy.

This paper identifies the sources of variations in the recycled plastic supply chain, the current limitations of the firms in tackling supply-oriented variations, and required changes in the decision system to mitigate supply variations in case of a closed-loop supply chain for a successful transition to the plastic circular economy. These new strategies will help maintain a stable supply of RP to avoid supply variation and mitigate the ripple effect on the production system for resilience. The research questions and objectives are given in the following two subsections.

1.1 Research Questions

1. What are the reasons for variation and associated uncertainties in the supply-oriented SCM of RP? **(RQ1)**
2. Why important to transform open-loop to closed-loop supply chain management in the circular economy of recycled plastic? **(RQ2)**
3. What are the improvements required in the current production and supply chain management to mitigate the effect of the uncertain nature of recycled plastic supply in closed-loop systems? **(RQ3)**

The structure of the manuscript is as follows. This is the Introduction section considering the background, problem statement, objectives, and explanation of the recycled supply chain. Section 02 is related to the literature on RP uncertainties, their impact on the production system, and strategies for mitigating variations. The methodology considers the systematic approach of finding improvement strategies to manage uncertain RP supply is given in Section 03. The findings and discussion are represented in Section 04 to discuss the sources of variations, closed-loop supply chain, and strategies for improvement of production and supply chain to mitigate the supply variations. The conclusion is given in the final section of the manuscript.

2. Literature Review

Linear plastic supply chain management uses virgin material for the processing of goods, and there is a less uncertain environment from the supplier end for production, design, sales, customers, and inventories due to homogeneity and less variance. The growing need and demand for circularity pressurize plastic manufacturers to incorporate RP into supply chain management. The RP is heterogeneous and may contain contamination, and the production firms were unable to anticipate the quality level, lead time, and cost of the RP. These changes in raw materials could disrupt the recycled plastic supply chain management by causing uncertainties in inventory management, production systems, product, design, and customer management systems. Production management and decisions are performing well if all the decisions are known and certain. But, if there is uncertain information about time, quality, and quantity from external suppliers without receiving updates on time, then firms cannot make the right decision at the right time.

Uncertainty in the production decision system can be divided into two types i.e., system and environmental uncertainty. is well-defined by (Ho 1989). System uncertainty is due to internal issues e.g., production, process, quality control, etc. whereas environmental uncertainty consists of the issues from the supply or demand side. These can disrupt the supply chain, however, there has been much attention given to dealing with demand uncertainty and rare research work performed to improve the production strategies for mitigating the supply-oriented variations. Companies are more oriented towards flexibility from the demand side and thus they do not have enough ability to absorb complexity from the supply side. Uncertain supply of recycled plastic can be managed from two dimensions i.e., by identifying and managing the source of variation in the supply chain to eliminate them and secondly by improving the production system with flexibility in inventory, processing, data management, and product design, to absorb the supply variation. This paper provides a generic framework for firms to develop an infrastructure for a closed-loop supply chain by identifying the sources of variations and helping to improve the production system to

achieve resilience by mitigating supply-oriented variations.

Various researchers worked on the challenges and risks faced by industries when transforming from linear to circular supply chain systems. Milios et al. (2018) studied plastic waste in the Nordic region and identified barriers to the circularity of plastic products. It is found that the supply and demand of recycling plastic, and market demand are the major challenges, however, the main hotspot is low demand due to price. In this direction, Johansen et al. (2022) reviewed the plastic supply chain from a recycling perspective and studied the design, production, usage, end-of-life, and value chain phases of plastic using the circular model. They concluded that the most significant challenges in the plastic life cycle are the contamination of waste and the widespread use of the composite material in design and packaging. Stingl et al. (2023) worked on the uncertainties in circular business innovation for recycled plastic and analyzed four key challenges i.e., quality, regulations, economics, and market uncertainties of the plastic. Moreover, the open loop circular plastic part of RP consists of unknown plastic quality with more variability where the chances of alignment with the production system are too low. In that case, systematic information sharing, and integration of supplier and processing firms are required to align the quality of raw material with the capability of the production system for the resilience of plastic supply chain management (Rojo et al. 2018). The transformation towards the circular economy is necessary to mitigate the negative environmental effects of plastic waste, but the production systems and supply chain management must be resilient to internal and external uncertainties.

Production systems have with time become much better at dealing with the challenges from uncertainty and variability through a range of different approaches. These strategies include product design, process design, inventory optimization, and a flexible production system. The safety stock approach, also called buffer inventory, increases the inventory level against expected uncertainty. Dellaert and Jeunet (2005) studied the impact of the positive lead time on the multi-lot-sizing rule and found that it can used instead of safety stock. Gurnani and Gerchak (2007) worked on random lead time to manage the materials from various suppliers. Mohammadi (2020) solved the issues of hazardous material supply under disruption and uncertain demand by optimizing the lot-sizing and scheduling problem. Gozali and Ali (2022) considered plastic jar companies to optimize the cost by formulating safety stocks, MRP, and lot size for the forward loop supply chain. Flexible settings in the production system are also required to deal with this uncertain supply. Angkiriwang et al. (2014) worked on flexible supply chain management by using buffering and redesign strategies of coordination to manage uncertainty. Wang et al. (2016) develop a framework and design the flexibility of an optimized operation for a supply chain network in the face of uncertainty. Hallack et al. (2022) systematically designed a recycling approach and mentioned challenges, principles, factors, and methods for eco-design of automotive exterior plastics.

Researchers in collaboration with industries and academia are working on supply chain and production efficiency with uncertainties and variation, however, still, there is no research work performed on the consequences and impact of the addition of RP in the supply chain and how to overcome these issues. This research first analyzed the causes of variation in the supply of recycled material. We recommend the firms transform their supply chain to a closed loop to manage the high level of uncertainties and variations resulted due to the addition of recycled plastic from the supplier side to provide a good quality product at the right price and at the right time to the customers. The transformation of the supply chain is possible by designing a robust production system with a supply chain infrastructure to manage the supply-oriented variations. This research focuses on the possible challenges associated with the production due to plastic recycling content and provides proactive strategies in dealing with them for the resilience of the closed-loop supply chain. A framework structure is developed for firms to consider potential decisions in a closed-loop supply chain of recycled plastic to manage the supply-oriented variations.

3. Methodology

The research methodology for this study encompasses a multifaceted approach aimed at investigating the integration of circular plastics into supply chain management while addressing challenges and maximizing opportunities. The study begins with establishing a foundational understanding of circular plastics, supply chain dynamics, and related factors. Subsequently, the impact of recycled plastic in the supply chain on the decisions and performance of the production system is carried out to understand how it is important to manage these supply-oriented uncertainties for the sustainability and circular economy of plastic. Building on this analysis, a robust conceptual framework is developed to guide the firms to make their production system and supply chain resilient against system and environmental uncertainties. The research culminates in the provision of actionable recommendations based on the findings. The dissemination of research outcomes through academic publications, conference presentations, and

engagement with industry stakeholders and policymakers serves to promote the practical implementation of circular plastics in sustainable and efficient supply chain management. This comprehensive research methodology ensures a holistic investigation of the topic, offering insights, and strategies that can benefit both academia and industry. The results will be documented in the form of the framework as shown in Figure 1.

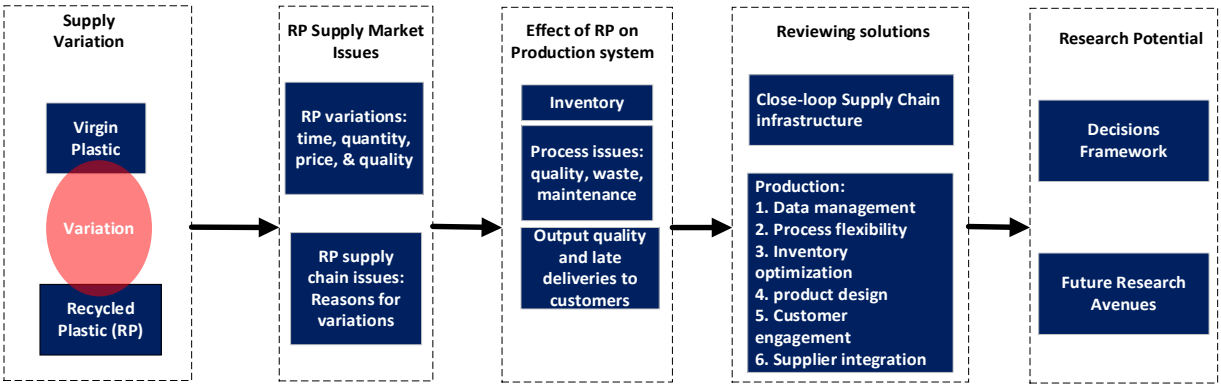

Figure 1. Research methodology of the proposed study

4. Research Findings and Discussion

The section is based on the analysis of the supply chain of RP, assessing the sources of the variations, closed-loop supply chain challenges, and required strategies with recommendations for the firms to achieve resilience in production and supply chain against uncertain supply for the successful circular economy of RP.

4.1. Source of variations in the recycled plastic supply chain and associated uncertainties

Corresponding to RQ1, the section provides a source of variations in the current RP supply chain. Recycled plastic (RP) is heterogeneous, and it may contain contamination and the production firms could not predict the quality level, lead time, and quantity of the RP. These variations among the raw materials could disturb the production plan which produced uncontrolled issues in inventory management, production, final product, distribution, and demand fulfillment to disrupt the recycled plastic supply chain management. The variations in the supply of RP at the upstream level are because of various reasons. The circularity in the plastic industry is a new and under process of research and development. The unavailability of the suppliers in managing the new recycled plastic as a raw material is one of the reasons for variation. Despite the interest of the government, institutions, and world organizations, we are still far away from achieving a plastic circular economy. Incineration firms are more developed and mature in tackling well plastic waste but that is not sustainable because of the maximum carbon emissions. Take the example of the United Kingdom, where only 9% of plastics are recycled and a large fraction of collected plastic is incinerated (Khaled and Christoph 2021). In addition, Denmark is also providing room for plastic recycling, where 57% of collected plastic waste is incinerated and only 13% is collected for recycling (McKinsey&Company 2019). Competition exists among suppliers for incineration and recycling. Due to large waste incineration overcapacity, development, and cost-benefit advantage, investors are more interested in incineration as compared to recycling plastic which negatively affects the environment more because of carbon emissions. As a result, the availability of recycling material is short at the supplier's end, and this may cause variations in lead time and the required quantity of RP supply.

The recycling plastic research is in a growing phase and the suppliers are inexperienced and new in the market. Firms cannot make a relationship with a few trustworthy suppliers. Small and new RP suppliers lack the technology for sorting and separating waste from recycling plastic. They are also required to align the quality of the RP with the requirement of the production using a cross-functional information system (Swink and Schoenherr 2015). Supplier integration with the production firm is significant in the context of the circular economy (Masi et al. 2018).

The quality level of the RP as a raw material is also one of the causes of uncertainty in production and supply chain management. The RP plastic coming from closed-loop and open-loop supply chains is not similar in properties to the virgin material. Open-loop suppliers are collecting plastic waste from different sources that may contain contamination and poor-quality plastic material because of poor sorting techniques (Larder and Hatton 2022). In that case, sometimes

the firms are compelled to take the RP from these suppliers after compromising on the quality because of limited availability, which affects the quality level of receiving RP and will cause uncertainties in production and the quality of the product. Few industries are more concerned about the quality of the product e.g., food industries and medicines because of the application of plastic products which are exposed more to the health and safety of the users. There are numerous chemicals in primary and secondary plastic products (recycling), which are hazardous to the environment and health (Groh et al. 2019). The increasing RP in plastic products may result in bad consequences for the health and safety of users (Cook, Derks et al. 2023).

Finally, plastic processing firms lack the required capability of flexibility in production, which is also a barrier to absorbing the variations from the supply of RP, which further creates challenges to other important decisions. Firms face challenges in developing strategies to cope with the uncertain supply of RP. The entire supply chain becomes more uncertain, and the traditional optimization calculations cannot provide an effective solution. The entire supply chain management must be capable of handling this heterogeneous raw material without disruption and the production strategies are required to cope with the uncertainties produced due to variations of RP.

4.2. Transforming from an open loop to a closed-loop supply chain

Corresponding to RQ2, the section provides how a closed-loop supply chain provides better results in a supply of RP as compared to the open-loop supply. Sustainability requires the utilization of circular plastic obtained by recycling plastic to replace or reduce the consumption of virgin plastic as a raw material (Jeswani et al. 2021). Recycled plastics (RP) generally come from open-loop and closed-loop supply chains. The firm is itself responsible for the closed loop RP and collecting it from the customers after its useful life for recycling. On the other hand, the open loop RP is provided by the recycling suppliers who are collecting the plastic from many sources for recycling. It is evident that the closed loop RP inherently consists of similar properties with less variation as the virgin one while the open loop RP is quite different from the virgin raw material. The RP in both cases cannot replace the demand for virgin material and RP is often used as a constituent in less proportion to the virgin raw material (Cimini and Moresi 2018). The supply chain concerns produced by upstream suppliers are related to unstable prices, unavailability, and poor quality while the demand is also variable depending on the transition and awareness of the customers toward green products (Kurowski et al. 2022). On the other hand, the production system is unable to absorb these variations and it causes maintenance issues and waste. These variations at the end affect the product quality, prices, and on-time delivery due to disruption and volatilities in supply chain management. The firms in the case of the closed-loop supply chain can control and manage the decisions of production planning and control including product design, supplier relationship, supply chain infrastructure, customer engagement, and technology management for information sharing. The illustration of the open-loop and closed-loop supply chain is well illustrated in Figure 2, where the ripple effect impacting the production system is explained by Dolgui et al. (2018) and Dolgui and Ivanov (2021) is also given in Figure 2.

Due to these issues in the open-loop supply market and the ripple effect on the production system, plastic firms are recommended to transform their supply chain from open-loop to closed-loop supply chain management to mitigate the supply variations because of the poor supply market of recycled plastic. The challenge of the closed-loop supply chain is to design an infrastructure for collecting products from the customers after the end of usage (EOU) life. The infrastructure includes facilities for contacting customers, collecting, cleaning/ sorting, storing, transporting, and recycling the used products to receive the recycled plastic with low variations in quality (because of recycling from the same plastic product), in quantity (because it will be depending on the capacity of infrastructure), and in lead time (because the whole returning process is performed by the host company). In this case, the recycled supply may still have variations and may not be like the virgin material, however, it will be better than the one received from the open-loop supply chain. That is the reason, we tried to assess the weak ends of the production system and analyze the significant decisions in the production required to manage the inherited variation in the supply of RP.

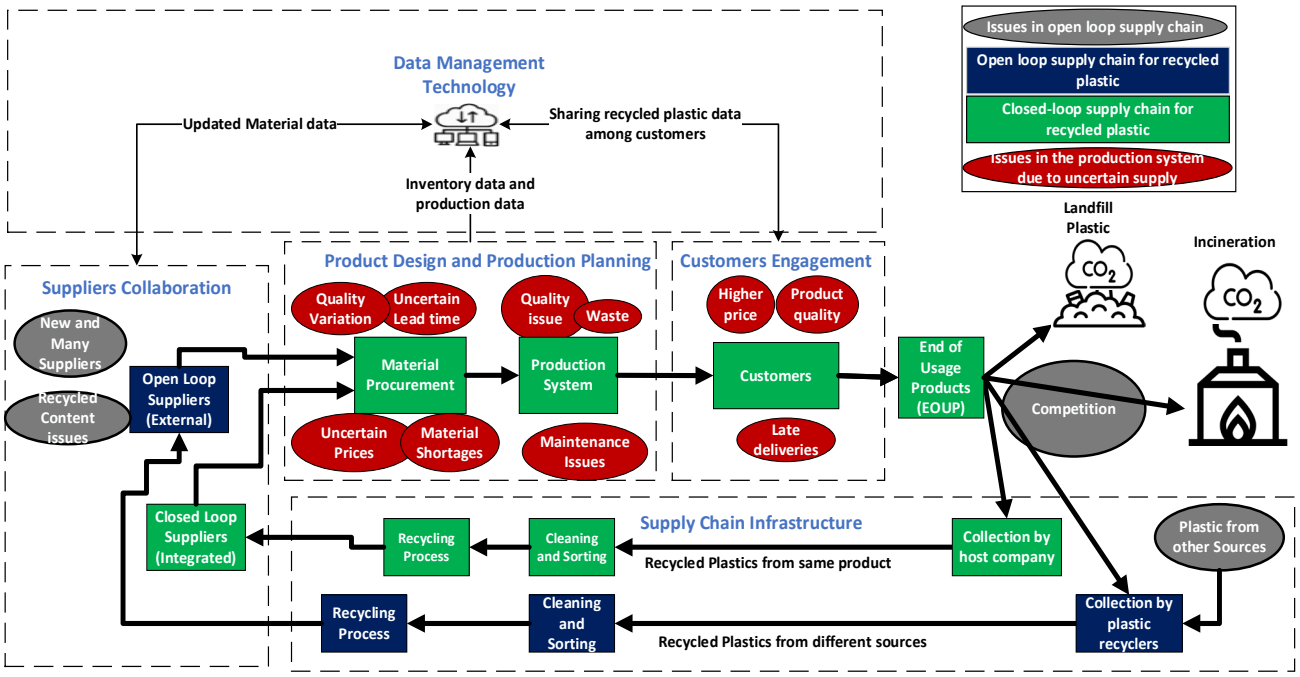

Figure 2. The representation of open-loop and closed-loop supply chains for recycled plastic by identifying sources of uncertainties and associated issues in production.

4.3 Strategic changes are required in the production system to deal with the uncertain supply of recycled plastics in the closed-loop system

Corresponding to RQ3, the section provides significant changes in the production system to deal with uncertain variations in the supply of RP. For the resilience of the circular supply chain of RP, the firm must understand the negative effect of environmental uncertainty on production planning due to supply variations and what are the control levers to mitigate the impact. Challenges due to the increasing demand for RP in the supply chain make it difficult for plastic firms to maintain and sustain the smooth flow of goods from supply to customers. The whole supply chain is disrupted but the problem is to find significant decisions at a strategic level to improve the flexibility and resilience of the production system and supply chain. First, the impact can be lowered by transforming into a closed-loop supply chain to eliminate the major sources of variations in open open-loop system. Secondly, significant decisions are required at a strategic level to improve the resilience of the production system and supply chain through data technologies, product design, production planning, customer and supplier collaboration, and developing an infrastructure to bring back the maximum percentage of plastic production. The structure of the significant decisions at a strategic level to mitigate the uncertain supply of RP in a closed-loop supply chain is illustrated in Figure 3. Ultimately, production control, product design, customer information, and supplier management are also affected due to the uncertain supply of raw materials as a combination of RP.

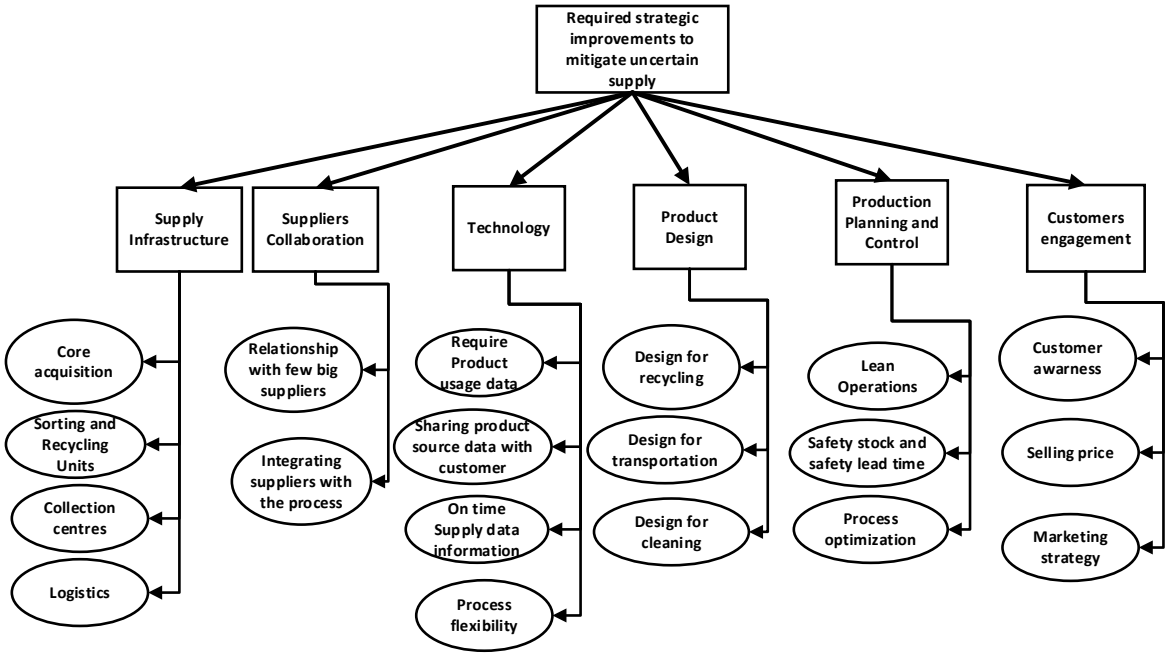

Figure 3. Improvements are required in the production and closed-loop supply chain to mitigate the effect of uncertain supply of the RP.

Supply infrastructure.

Supply infrastructure includes core acquisition, sorting, recycling, collection centers, and logistics of plastic products. It is one of the biggest challenges for companies to collect the product from the customers after useful life called cores and it requires facilities and resources because it requires huge capital and a strategic business plan for the utilization of optimal resources. There are various takeback strategies companies are using in collaboration with their retailers to provide a platform for returning used products e.g., incentives for swapping old with new, incentives for returning, separate collection bins, etc. It is also essential to optimize the number of collection centers required for the storage and sorting of the product, which depends on product type (size, shape) and return rate. The third step is required to optimize to provide optimal logistics to transport the used product from collection centers to the recycling plant from different regions. There are two types of recycling i.e., mechanical, and chemical recycling (Kubiczek et al. 2023). Mechanical recycling is converting the plastic product into granules using extrusion or molding, whereas chemical recycling is utilizing high temperatures and converting the product into granules using depolymerization and chemical reactions. Chemical recycling produces a good quality of recycled material due to chemical reactions, however, due to high heat, they are producing a negative environmental impact (Jiang et al. 2022).

Suppliers' collaboration

Suppliers and manufacturer relationships are immense to manage the variations by coordination. Suppliers must be aware of the process capability and flexibility of the production firms to provide the required recycled material. The processing firms are required to align the quality of raw material with the capability of the production system for the resilience of plastic supply chain management (Rojo et al. 2018). Prosman and Wæhrens (2019) draw a significance of integration between suppliers and manufacturers to manage the variation in the quality of the receiving raw material in case of industrial symbiosis, they found better results in managing supply variation, when integrating suppliers with the requirements and capability of the production in cement processing firm. The production firms must integrate suppliers in their production planning process to ensure the quality of the supply with the capability and flexibility of the process to deal with the quality variations of RP.

Technology

There are two types of technologies required in the production system i.e., the first is the process technology for the flexibility of the production system to change the settings of the machines and scheduling automatically without increasing the setup cost e.g., automation, flexible systems. The second one is related to information technology,

which is nowadays significant for timely decisions based on supply information and customer engagements e.g., Industry 4.0, RFID (Olsen and Tomlin 2019), blockchain (Govindan 2022), digital passport (Jensen et al. 2023), etc. The role of information technology is significant in getting updated data from suppliers related to delays, uncertain quantities, and the sources of the additives and materials included in the recycling process. It is also important to inform the customers through information-sharing technologies about the source of the data, recycling percentages, changes in the quality, and delays in deliveries.

Product design

Now, the EOLP strategy of circular economy is a significant phase of the product life cycle, and product designers are advised to incur the remanufacturing attributes during the designing phase to provide a promising business with environmental, economic, and social advantages. In the case of recycling, the designer must understand the requirements of the recycling operations (Mechanical or Chemical) feasible for their EOLP. The product must be designed for the recycling process, the selection of material must consider the easiness of cleaning and separation, and the size and shape must be set for a lower cost of transportation. The design of the product depends on the complexity of the product structure, size, shape, handling, aesthetics, finishing, etc. (Hallack et al. 2022).

Production planning and control

The production planning and control strategies include inventory management, quality management, lean operations, and process optimization for the management of uncertain supply. The uncertainties in the plastic processing/ production system can be avoided by placing an optimal storage buffer of the varieties of the CP in raw material inventory with a minimum cost of holding. It will require data on the available material supply and requirements of the plastic processing firm. Lean operations include tools and techniques e.g., Kanban, 6 Sigma, 5S, Just in Time, Cross training, Quality tools, etc., that seek to reduce different types of waste in the processing (Kurilova-Palisaitiene et al. 2018).

Customers' engagement

It is also a call for customer engagement to understand specific demand specifications at a granular level, and hereby to understand the important constraints and where leeway for variation can be found and accepted. The organizations must help the customers understand the changes in the product due to the transition from a linear to a circular supply chain of RP.

5. Conclusions

The research work goes through reviewing the challenges faced by the current plastic firms to manage the RP in the supply chain. There are many reasons for these uncontrollable variations from the suppliers' end and associated uncertainties in production, which affect the resilience and performance of the production system. It analyzes how the current production system is rigid and incapable of managing the RP consisting of heterogeneous recycling content. Mitigation strategies are recommended for the firms to deal with the uncertainties produced by the variations in the supply for the consumption of RP without disruption for the successful transition towards the circular economy. It is also recommended to transform the supply businesses from an open-loop to a closed-loop system by developing a supply chain infrastructure. Transitioning to a circular economy requires a fundamental shift in how firms manage production processes and supply chains. By adopting flexible production systems, information technology for sharing data with suppliers and customers, product design for recycling, process optimization and flexibility, lean operations, and supply infrastructure, firms can better manage the uncertainties associated with heterogeneous recycling content. Coupled with innovative business models and supportive regulatory frameworks, these strategies will enable firms to mitigate disruptions and achieve a successful transition towards a more sustainable and circular economic model.

The research is based on the literature reviews and the results are significant for decision-makers to transform their supply chain from a linear to a circular economy in a closed-loop supply chain of RP. There are future research avenues associated with the findings of the work. The variations and associated uncertainties can be identified and ranked for the benefit of the firms to consider only significant challenges for further improving the production system. Multicriteria decision tools, Pareto fronts, fuzzy systems, and other techniques can be utilized to identify and prioritize significant decisions. Systematic data collection using designed questionnaires and conducting interviews with industrial experts are required to further extend the application of the work for managing supply-based variations. These uncertainties can be converted into measurable risks to provide proactive strategies related to production and supply chain to avoid the variations and associated uncertainties using risk management analysis.

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