Industry 4.0 for Circular Plastic Flow Improvement: A Systematic Literature Review and Conceptual Framework

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ABSTRACT

Plastics are used for various products and applications but the production and waste management operations need to be addressed to ensure sustainability goals can be achieved. Circular economy aims to reduce waste through circulation, and technology innovations are one of the enablers for this transition. This research interprets Industry 4.0 applications and associated adoption factors according to the waste hierarchy and Political, economic, social, technological, legal and environmental (PESTLE) analysis. A conceptual framework is then constructed to illustrate the factors and acknowledge the systematic perception for solution development. The Global Supply Chain Forum model is approached to visualise technology applications based on the supply chain processes, as well as demonstrate how the framework can be utilised. The framework is designed for various sectors to understand their operations in the context of these factors and determine solution approaches. This framework also emphasises the necessity of acknowledging potential impacts over time to ensure these aspects are addressed and that the solution is effective. Limitations of this framework include the need of further research to ensure factor generalisation for all sectors when the technology of interest is considered for solution development.

Keywords: circular economy, plastics, supply chains, Industry 4.0

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1 INTRODUCTION

Plastics are used in different applications, ranging from packaging to aviation [1], [2]. However, these materials also lead to environmental concerns, such as pollution in oceans and climate change [3], [4].

1.1 Background

Plastic waste in oceans has physical influences on organisms and the life cycle releases emissions during production and waste management [1], [4], [5]. Strategies, such as reuse and recycling, require evaluation to improve waste management and avoid further complications for ecosystems in the future [6]. Circular economy (CE) has the objective to eliminate waste through these strategies, as well as design and maintenance [7].

CE acknowledges plastics as technical materials due to their negative impacts on the environment [8], [9]. Technical resources can imply materials with durable characteristics, meaning these materials must be circulated to enhance product life cycles and utility for waste reduction, as well as value creation. Product designs, for instance, could be altered for reuse [10]. Recycled materials could also be considered for product development.

Kirchherr et al. [11] identify technology innovation as an enabler for CE transition. Technologies can monitor materials in the system and enhance stakeholder collaboration for CE transition [8], [9]. These capabilities may be essential for the plastic value chain since a holistic perception is necessary to acknowledge concerns influencing circularity [12], [13], [14]. For example, manufacturers must understand how the product's design could influence recycling [15]. Research has analysed Industry 4.0 to promote CE practices with plastics, such as additive manufacturing for waste valorisation [16], [17]. However, the systematic perception appears to be limited in research with respect to the waste hierarchy.

Waste hierarchies may be necessary to ensure a holistic perception across the supply chain (SC) for CE transition [18]. Furthermore, using waste hierarchies are important for encouraging companies to aim for optimal SC performance in sustainability, meaning waste reduction should be concentrated for transition. Waste prevention can reduce waste and associated expenses for collection, whereas recycling uses more energy for processing, which impacts the environmental and financial performance [19], [20]. However, Dijkstra et al. [20], having categorised business models addressing plastics based on the waste hierarchy, conclude that recycling is common compared to the other strategies in reuse or prevention. However, recycling alone in a specific area of the SC is not sufficient compared to a systematic transformation for CE implementation [18]. This aspect may indicate that the business models' sustainable performance with plastics requires improvement for CE transition [20]. Nevertheless, research analysing Industry 4.0 for plastic waste management (PWM) and CE provides limited information or a lack of content regarding waste hierarchies [16], [17], [21].

1.2 Research problem

This research focuses and extends the studies by Sahu et al. [22], Lei et al. [23], and Bag et al. [24] to address the lack of a systematic perception through the application of the waste hierarchy and various adoption factors. For example, Lei et al. [23] performed a systematic literature review (SLR) and analysed the influences of Industry 4.0 on CE to acknowledge the technologies' capabilities in a holistic perception for CE implementation. The applications were arranged according to CE practices, such as waste reduction, maintenance and recycling. The authors included a study from Nara et al. [25] evaluating Industry 4.0 in the plastic sector and indicated that the Internet of Things (IoT) could be approached to reduce expenses for CE. Nevertheless, Lei et al. [23] did not assess factors for adoption as comprehensively as Sahu et al. [22] or Bag et al. [24].

The lack of a systematic perception hinders opportunities to enhance the sustainable performance since this viewpoint assists in managing barriers preventing transitions throughout the value chain tiers from raw material production to plastic recycling [26]. Sahu et al. [22] evaluated factors regarding CE and Industry 4.0 adoption, ranging from concerns influencing employment to the need for government involvement. These authors did not consider the waste hierarchy for the technologies and acknowledged that research was limited regarding SC management for the technologies and CE. Bag et al. [24] assessed Industry 4.0 enablers for sustainability in SC, yet waste hierarchies and the plastic value chain were not analysed for transition.

This research aims to extend the research from [22], [23] and [24] since these studies indicate potential opportunities to enhance the holistic perception of the plastic value chain for adopting Industry 4.0 and promoting CE transition. For instance, Sahu et al. [22] acknowledged various factors for CE and Industry 4.0 technologies but did not concentrate on the plastic value chain. This aspect is essential since factors influencing circularity can relate to various considerations, such as economic, technological and legal concerns, emphasising the need for a holistic perception to promote circularity [12]. Lei et al. [23] and Bag et al. [24] also did not consider plastics as the main concern for Industry 4.0 adoption. Therefore, this research aims to extend these studies to enhance the holistic perspective and acknowledge factors influencing Industry 4.0 adoption for plastic circularity.

1.3 Research question

This research aims to improve the systematic perception for Industry 4.0 adoption and enable circularity in the plastic value chain. However, Sahu et al. [22] claim that Industry 4.0 adoption may not be the same for each organisation as the factors depend on the country or sector of interest. For instance, obstacles for India include concerns affecting employment and the need for integration regarding processes and digital technologies. Denmark may experience barriers related to employment considerations yet Denmark has more drivers for adoption compared to India, including technology accessibility to promote circular flows. Developed countries have also conducted more research on the technologies and CE, whereas the research for developing countries is in the initial stage.

Companies may also need to acknowledge the context of their environment for Industry 4.0 adoption since certain organisations, such as small businesses, may select one of the various technologies to satisfy budget constraints [23]. These aspects may imply that companies need to interpret their system in a holistic viewpoint to understand and manage the respective factors influencing Industry 4.0 adoption for CE transition. Therefore, these concerns are addressed through the following research question: "How could organisations implement CE practices using Industry 4.0 technologies to improve PWM in SCs?".

The research design explains the selected concepts to answer the research question, followed by the research methodology, SLR and a conceptual framework. The SLR is performed since Lei et al. [23] considered an SLR to acknowledge Industry 4.0 influences on CE in a holistic perception. This research conducts an SLR to understand the technology applications in this perception for PWM, as well as to determine factors impacting adoption for CE transition. The information is used to develop a conceptual framework, concluding with future research opportunities for refinement and improvement.

2 RESEARCH METHODOLOGY

2.1 Research design

The research design approaches the waste hierarchy and PESTLE analysis to design a conceptual framework consisting of the holistic viewpoint and adoption factors [27], [28]. The research also considers alternative solutions when the technology is not applicable or available, as well as the Global Supply Chain Forum (GSCF) model to visualise Industry 4.0 applications for PWM [29], [30].

2.1.1 Circular economy and waste hierarchy

CE and the waste hierarchy share similarities where CE includes a value creation approach to extend product life cycles and promote cost-saving opportunities through maintenance as the inner loop, followed by reuse, refurbishment and recycling [8], [9], [11]. This order is due to the increasing expenses of using energy and resources for processing. The waste hierarchy prioritises waste prevention for environmental performance and economic benefits since prevention promotes cost-saving opportunities for waste collection and processing [20], [27]. Recycling, however, increases the expenses and reduces these benefits. Therefore, maintenance and waste reduction can be more effective than recycling in PWM, which aligns with Kirchherr et al. [11] regarding the CE objectives in waste reduction and maintaining value.

The hierarchy promotes incremental change and illustrates which strategy may be preferable, such as recycling as a more appropriate alternative than recovery or disposal, rather than indicating reduction as the overall objective in waste management [31]. Incremental adaptations alone are not sufficient for CE since systematic transitions have greater impacts on sustainability performance [11]. However, upscaling is an enabler for CE transition. This enabler may need to be considered for CE solutions in the plastic value chain as Lisiecki et al. [32] indicated that factors can relate to different perceptions, such as social or policy concerns, and that these factors must be managed to promote scalability. This statement aligns with the need for a holistic perception of the plastic value chain to ensure circular flows and sustainability [13], [26]. Therefore, the waste hierarchy is approached to not only arrange Industry 4.0 applications according to each strategy, but also to acknowledge the systematic perception through incremental change and upscaling as progression toward potential waste reduction.

2.1.2 PESTLE analysis

Research has identified factors in different viewpoints, such as legal, environmental, ethical and organisational considerations, for Industry 4.0 adoption [22], [33]. Sahu et al. [22] observe that the factors depend on the sector and location of interest. Nevertheless, the factors can be grouped into categories for evaluation and determining how these factors could impact the overall SC. For example, Siltaloppi and Jähi [26] identified obstacles for sustainability throughout the plastic value chain in market, SC, societal and technological aspects. The low recycled plastic supply for manufacturing is due to the need for advanced technologies and heterogeneous plastic waste complicating the mechanical recycling operations. Challenges for upscaling include demand uncertainty and investments for capacity development.

Paletta et al. [12] interpreted obstacles for plastic circularity from economic to socio-cultural concerns. CE initiatives would also need to consider the various factors for scalability [32]. Sahu et al. [22] analysed legal aspects, economic drivers, and obstacles in environmental perspectives. Therefore, factors can be categorised to group the information and acknowledge the technology applications in a holistic perception for solution development.

Chavez and Sharma [28] assessed a closed-loop SC in Mexico with respect to the PESTLE analysis to understand the conditions and evaluate each stage from legal to environmental concerns. This technique assisted in determining the SC performance and whether the system is applicable through different perspectives, such as frameworks in legal perceptions. Therefore, this technique is used to identify and group the main factors in adopting Industry 4.0 for any sector or country, thereby supporting and acknowledging the holistic perception for solution development and implementation.

2.1.3 Alternative solutions

Alternative solutions include chemical recycling, bioplastics and organisational culture as suggestions when the technology is not applicable or available for PWM [34], [35], [36]. This aspect is considered since Dijkstra et al. [20] have identified business models with different solutions to manage plastics sustainably. For example, business models may use additive manufacturing while the other models may refer to bioplastics or include communities in sustainable practices. Furthermore, Dijkstra et al. [20] assigned the waste management strategies to each business model case, indicating that models may consider different sustainable approaches, such as combining recycling with reuse or prevention.

Lisiecki et al. [32] evaluated various CE initiatives for plastic circularity, ranging from plastic bans to blockchain in waste sorting, bioplastics and chemical recycling. Bag et al. [24], citing Sung [37], found that companies may experience challenges regarding technology adoption since impacts could affect a SC's economic performance. Therefore, companies may consider different approaches besides Industry 4.0 for PWM and CE transition. These three alternative solutions are considered but not evaluated extensively since Industry 4.0 is the main topic for the research scope, meaning the alternatives are suggestions for further investigation.

2.1.4 Global Supply Chain Forum Model and Industry 4.0 Applications

Bag et al. [24] could not identify research regarding a framework providing a systematic perception of SC and Industry 4.0 for sustainability. However, the GSCF model includes eight core processes and various activities in each process that must be planned for the functions to operate accordingly and achieve SC objectives [29]. For example, manufacturing operations need information regarding product designs to determine the required capabilities and flexibility. Hazen et al. [30] and Rebelo et al. [38] used this model for CE motivation and IoT applications. Therefore, this research considers the GSCF model to illustrate Industry 4.0 applications throughout the SC network and demonstrate the conceptual framework's purpose for solution development. Figure 1 illustrates Industry 4.0 applications from the SLR according to the GSCF model's process descriptions and SC activities from Croxton et al. [29] and Hazen et al. [30].

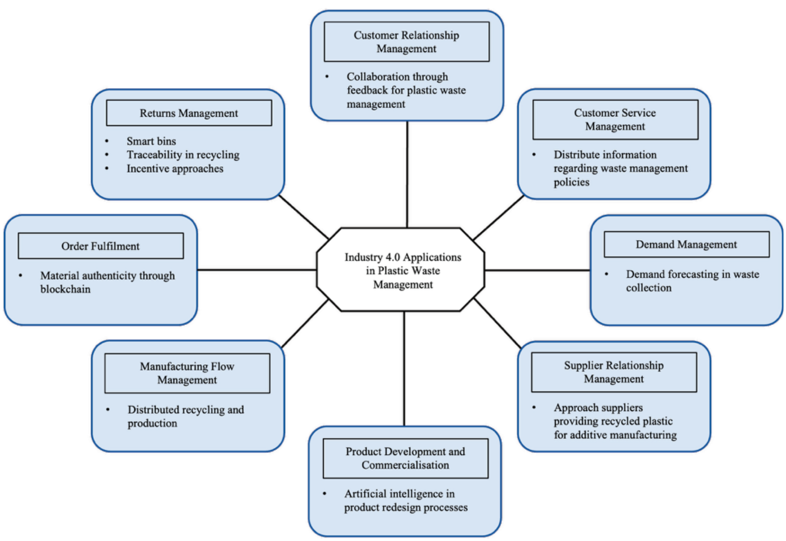

Figure 1: Examples of Industry 4.0 applications from the SLR according to each process in the GSCF model

IoT applications, for instance, can provide opportunities for governments to develop and distribute policies for waste management [39]. Residents can view the regulations and provide feedback for recycling improvement. Activities in returns management for CE involve collaboration and visibility enhancement throughout the SC [30]. Customer service management provides product information to the customers; relationship management needs to focus on customer involvement for CE transition [29], [30], [40]. Therefore, SC processes may consider IoT applications for these processes.

Lei et al. [23] identified essential technologies, such as IoT, artificial intelligence, big data and additive manufacturing for CE motivation. These technologies, as well as blockchain, have been analysed to promote plastic circularity [16], [17], [32]. While Lei et al. [23] appear to consider only one study, that of Nara et al. [25], regarding Industry 4.0 for sustainability with plastics, this research focuses on all five of these technologies for circular plastic flows.

2.2 Research methodology

This research follows the Double Diamond methodology of the Design Council [41], [42] to perform an SLR and design the conceptual framework. Clune and Lockrey [43] used the Double Diamond to identify sustainable strategies in the aged care sector. These authors considered divergent and convergent thinking to investigate the problem, promote collaboration, and to determine solutions for effective environmental performance in sustainability. The research adopts this framework to apply these thinking approaches during the SLR and conceptual framework construction phases.

The SLR was performed in the first two stages of the first diamond: "Discover" and "Define", to interpret literature regarding Industry 4.0 for PWM. The PESTLE analysis and waste hierarchy were used to assess the applications for adoption factors and waste management strategies. The SLR steps from Pollock and Berge [44] were conducted for the procedure, including the Critical Appraisal Skills Programme (CASP) checklist [45] as a quality assessment. Guidelines from Snyder [46] were used to address the required SLR elements.

The second diamond was then conducted for the conceptual framework design in the "Develop" stage. "Deliver" is the final stage where the solution is evaluated and implemented [42]. The framework is described and illustrated using the GSCF model for interpretation. Implementation is beyond the scope of this research.

3 SYSTEMATIC LITERATURE REVIEW

The first diamond involves two stages: "Discover" and "Define", to interpret the problem comprehensively and determine areas for solution development [41], [42]. The SLR procedure began with the research objective and a search of articles to identify terms and databases for the "Define" stage [44].

3.1 Discover

Emerald, ScienceDirect and ProQuest were selected to search for resources. Table 1 displays search terms according to the research question and various sources to expand the search field, such as "circular plastic economy" and "digitalisation" [16], [47], [48]. The advanced search was included for the topic in plastics and waste management to focus on abstracts with these terms. The other topics did not have any specific requirements for the search string. Filters were used in ProQuest to list peer-reviewed studies in English. Filters were not applied in the other databases.

Table 1: Search terms for the SLR

Topics	Search Terms
Technologies	"industry 4.0", "fourth industrial revolution", "digitalisation", "additive manufactur*", digitalization", "3D print*", "digital*", "knowledge-based system*", "manufactur*", "technolog*", "smart", "IoT", "internet of things", "industrial internet of things", "industrial IoT", "blockchain", "machine learning", "artificial intelligen*", "AI", "big data"
Plastics and Waste Management	"polymer*", "plastic*", "circular*", "circular plastic economy", "manag*", "waste", "municipal waste"
SCs	"supply chain*"
Organisations	"industr*", "organisation*", "compan*", "organization*"

Figure 2 gives an overview of the criteria for article selection in each SLR phase. The screening phase, for instance, removed non-peer-reviewed resources and excluded inaccessible studies, except for three textbook chapters [49], [50], [51]. The eligibility phase included articles with any of the five Industry 4.0 technologies of interest [52], [53], [54]. Paras et al. [55] considered genetic algorithms for clothing. Textiles, trays consisting of polymer components, such as the inlay or coatings, as well as medical and packaging products, include plastics [2], [10], [52], [56]. The SLR process was documented in each phase with respective reasons for selection or exclusion on Microsoft Excel [47], [57], [58].

Sensitivity and specificity were applied in the screening and eligibility phases [47]. For example, abstracts were assessed in the screening process based on sensitivity to include potential studies applicable for the review after evaluation in the eligibility phase [47], [59]. The articles were analysed in the eligibility phase for relevance confirmation if the abstracts did not mention Industry 4.0 or PWM. Articles were added to the databases over time, meaning new articles were included until the end of the screening processes for each database. The new articles added after these dates were excluded.

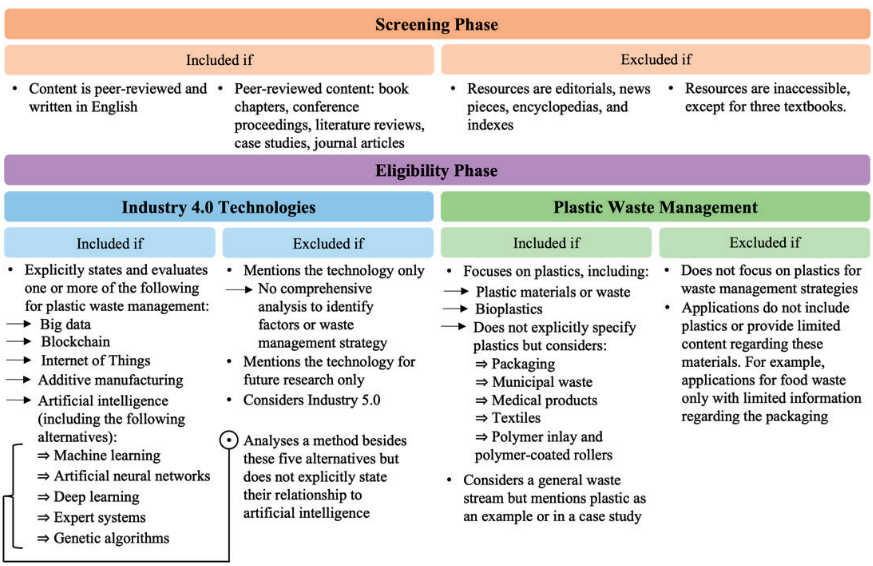

Figure 2: The screening phase and refined criteria for the eligibility phase

Figure 3 illustrates an adapted version of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart of the SLR [60].

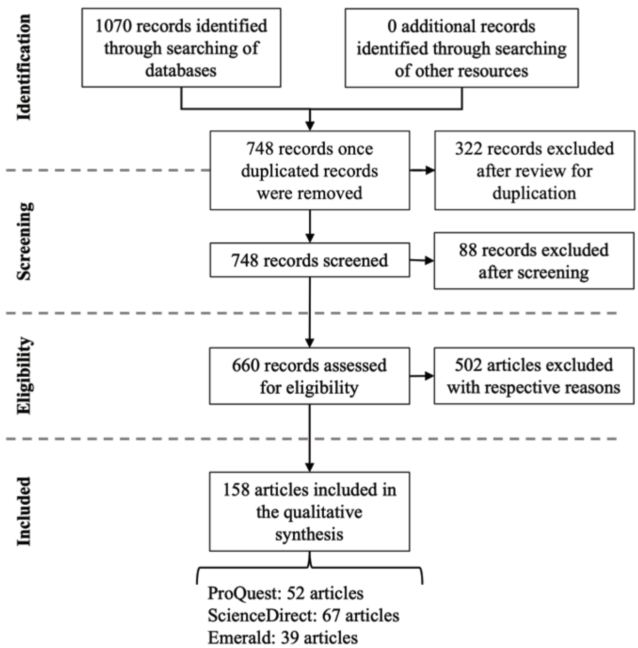

Figure 3: An adapted version of the PRISMA flowchart for the SLR [60]

Table 2 displays the timeframe for each database when the SLR was performed. Data collection and quality assessments were the next SLR steps performed in the "Define" stage of the Double Diamond [41], [42], [44].

Table 2: The SLR timeline from identification to eligibility

Database	Identification	Screening	Eligibility
ProQuest	13 July 2024	13-16 July 2024	23 September - 7 October 2024
ScienceDirect	17 July 2024	17-22 July 2024	17-22 October 2024
Emerald	2 September 2024	2-6 September 2024	7-17 October 2024

3.2 Define

The CASP checklist was used to interpret the selected articles' quality since research has referred to CASP for the quality assessment [45], [61]. The included articles were assessed to determine whether the research objective was clear, as well as to acknowledge the content and result interpretation. For instance, Gonçalves et al. [62] satisfied the criteria in Figure 2 since the study discussed Industry 4.0 applications and focused on plastic sectors for a roadmap towards sustainability. However, the study provided limited information regarding result precision or quality assessments of the respective resources. The authors indicated the study is in the initial stages and requires further analysis for the roadmap. Therefore, this research includes the study due to the eligibility criteria while identifying the potential limitations according to the checklist for the SLR. Beall's list of predatory publications was used to identify potential predatory journals [63]. These resources were removed but not recorded in the SLR since these publications are flagged as potential predatory journals. PESTLE and the waste hierarchy were then applied to gather data from the selected articles for analysis.

3.3 Waste hierarchy for Industry 4.0 classification

Table 3 summarises examples of Industry 4.0 applications based on recycling, waste prevention and reuse. A record indicating which strategy may be common [20], was not included since certain studies consider more than one strategy for reuse and recycling [55].

Table 3: Examples of Industry 4.0 applications in the SLR, from waste prevention to recycling

Waste Management Strategy	Technology Applications to Manage Plastics
Waste Prevention	Additive manufacturing utilising bioplastics or addressing material savings [64], [65] Blockchain or IoT for maintenance strategies [52], [66] Ul Haq and Franceschini [67] evaluated literature regarding distributed manufacturing with big data analytics, additive manufacturing, IoT and artificial intelligence.
Reuse	Artificial intelligence in processes to redesign products for reuse [55]
Recycling	Additive manufacturing in distributed recycling scenarios [68], [69], [70] Blockchain for incentive initiatives and tracking applications [71], [72] IoT and artificial intelligence in waste management applications [39], [73]

Waste prevention can imply the use of different materials or waste reduction through life cycle extensions [19], [20]. IoT and additive manufacturing for waste reduction may relate to maintenance and material utilisation enhancement [52], [64]. The use of materials can improve the associated expenses through the printers [64]. Maintenance could assist with value creation opportunities through preservation [8], [9], [11].

Reuse relates to product designs with durable characteristics, as well as activities in repair or re-assembly [19], [20]. Artificial intelligence could be approached in redesign operations to enhance reusability of clothing components [55]. Recycling can transform the waste into resources and additive manufacturing has been evaluated for distributed recycling operations [19], [68]-[70].

Big data analytics may provide potential opportunities to optimise the value chain for CE transition in terms of digitalisation and traceability. For instance, Ul Haq and Franceschini [67], citing Zaki et al. [74], state that digitalisation includes big data analytics technologies and that advancements are promoting distributed manufacturing. Recycling companies refer to big data to understand the plastic flow according to the product's barcode [75]. Digitalisation is also evaluated in the plastic packaging sector for CE [76]. However, regulations are needed to enhance traceability and these legal aspects are considered as factors influencing Industry 4.0 adoption for PWM, which is discussed in the following section [75], [77].

3.4 PESTLE analysis

Factors for technology adoption are arranged according to each perspective in the PESTLE analysis. The purpose of the PESTLE analysis was to determine key adoption factors for an organisation in any sector aiming to utilise the technology for PWM and CE transition. The Sankey diagram in Figure 4 displays examples of factors from 134 studies for Industry 4.0, along with a count of the factors identified in literature. This count includes the articles that may be from potential predatory resources [63]. However, the following sections refer to studies that did not relate to these potential predatory resources. Classification considers factors such as energy consumption for environmental concerns [28], [78]. However, this research interpreted the factors at a high level since the factors can relate to an organisation's location and sector of interest [22]. Therefore, the research considered key words, such as "energy consumption", for further evaluation, and included additional aspects, such as quality concerns, for additive manufacturing [53], [64].

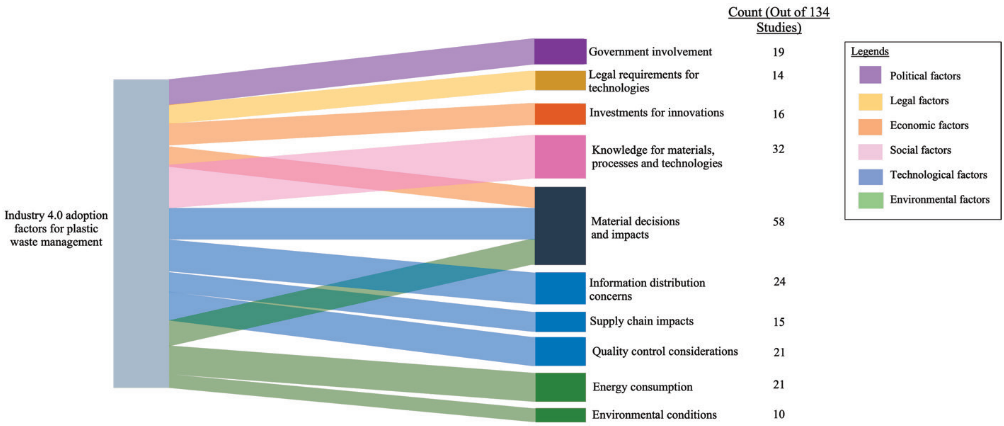

Figure 4: A Sankey diagram of possible factors for Industry 4.0 in PWM

The factors given in Figure 4 may imply challenges, requirements or impacts, depending on the study for PWM. For instance, additive manufacturing can affect SC flexibility performance and involve challenges related to the printed product's quality [64]. Tani et al. [53] and Chaudhuri et al. [79] suggest alternative approaches to address quality, such as competency or production enhancement. Biomedical sectors may also need to acknowledge legal aspects for utility due to health regulation concerns [53]. Nevertheless, this research has arranged the information according to each aspect in PESTLE to identify essential themes for adoption for any sector.

Factors in the Sankey diagram are discussed in the following sections. Dynamic aspects will refer to each factor category to illustrate how all these factors would need to be considered for the systematic perception and solution development.

3.4.1 Legal and political aspects

Companies may need to acknowledge potential legal concerns, such as regulatory restrictions for waste management, innovation, or health aspects [53], [54], [77]. Regulations in waste management may prevent a company's opportunity to conduct solutions for CE [77]. Biomedical sectors require certification to use the printers for valve production [53].

Intellectual property (IP) and standardisation may also require evaluation for the applications and PWM [53], [75], [80].

Organisations need to engage with stakeholders and enhance information exchange yet IP could imply collaboration challenges for CE transition [40], [75]. A potential approach to promote information exchange is the use of patents for value designs [53]. Policies could also be developed for information distribution concerns but these policies must also balance with opportunities for innovation [54], [75].

Standardisation is required for certain sectors, such as biomedical industries, since additive manufacturing implies different printers and associated performance for production [53]. The product design and quality would also need to acknowledge health regulations while using the printers for development. An example of potential standardisation is a combination of the printers with conventional manufacturing for product development [64], [79]. An interviewee in [53] explained that injection moulding is preferable for manufacturing products and reducing variation. Benthos Buttons used additive manufacturing to develop buttons from recycled plastic but the products' details required solutions [79]. This company then combined additive manufacturing with injection moulding where the printers create moulds and injection moulding manufactures the buttons from these moulds to control the variations.

Standardisation is also essential for recycling improvement [75]. The SLR identified existing standards related to additive manufacturing or waste management [39], [75], [79], [81]. Nevertheless, standardisation may require improvement to enhance plastic circularity and increase opportunities for utility in certain sectors [53], [75]. Furthermore, standards, as well as frameworks regarding legal aspects, are necessary for validating additive manufacturing in distributed recycling [68]. Therefore, government involvement is essential to develop policies for PWM improvement and Industry 4.0 adoption, as well as to assist in financial requirements for implementation [39], [54].

3.4.2 Economic aspects

Industry 4.0 applications may imply different economic performances, depending on the application and study. For instance, additive manufacturing in isolated locations could address logistics and manufacturing expenses [65]. Research has also analysed open-source approaches for economic considerations and distributed recycling [65], [68], [69]. IoT for maintenance strategies can reduce repair costs but decisions for IoT in waste monitoring may require evaluation to acknowledge expenses for implementation [52], [82]. Algorithm complexity can also impact the economic performance of blockchain applications [72].

Research would discuss investments for the applications, such as the use of the current hardware or open-source methodologies to address expenses [52], [65], [69]. However, financial requirements may imply challenges for certain sectors or companies aiming to implement innovative strategies for plastic circularity [54]. Governments may be required to assist organisations with this aspect.

Decisions regarding materials would incur expenses since costs between primary or secondary plastic may differ depending on oil prices and recycling operations [10], [34]. Material decisions can be considered for additive manufacturing in distributed recycling scenarios as the prices of these materials can be compared to determine the economic performance [69]. Market aspects may also need to be considered for recycled plastics and bioplastics, such as polylactic acid [34], [83]. These economic aspects, as well as environmental concerns regarding material decisions are illustrated in Figure 4. The market for recycled plastics and additive manufacturing may improve if distributed recycling development is concentrated [69]. Nevertheless, an organisation must learn how the secondary plastics should be utilised for additive manufacturing [79].

3.4.3 Social aspects

Knowledge of the materials, Industry 4.0 technologies and processes have been emphasised for the applications and plastic circularity [55], [75], [79]. For example, knowledge regarding recycled plastics could be essential in additive manufacturing applications for CE transition [79]. Training is necessary to implement the technologies [84]. Cultural aspects, such as lifestyles or behaviour, may also need to be considered for Industry 4.0 in PWM [54], [65].

Additive manufacturing applications must acknowledge values in cultural perceptions for utility in certain industries, such as reindeer husbandry sectors [65]. Behaviour regarding plastic waste may imply challenges for improving waste management [54], [85]. Waste management practices require customer participation to distribute the waste to collection centres for recovery, meaning behaviours may need to be considered for these practices [20]. Education and data aspects are also obstacles in Africa since stakeholders must understand the context of plastic waste for CE practices [54], [75]. Blockchain and IoT could be approached to encourage participation and collaboration through incentive initiatives and information exchange regarding waste management practices, respectively [39], [71], [72]. Blockchain could also assist with these obstacles through traceability to acknowledge and manage the product life cycle [54]. Therefore, stakeholder collaboration is a critical factor to be addressed for effective transition and digital applications could be approached for this requirement in terms of networks [86].

The informal sectors play essential roles in Africa for waste management and engagement with these stakeholders through the technologies could promote job creation opportunities [86]. However, companies may need to encourage stakeholders to adopt the Industry 4.0 technologies for their operations [79]. Tseng et al. [87], citing Kumar et al. [84], argue that employment concerns can imply hesitation in Industry 4.0 adoption. This concern for Industry 4.0 adoption is also considered in Africa and Korea [24], [37]. Organisations may need to determine strategies for encouragement, as well as to concentrate on training and improving awareness [84], [87]. Waste2Wear suggests adaptive approaches to address these concerns and implements education initiatives for blockchain in plastic recycling transparency [79]. Therefore, stakeholder collaboration, as well as training, is essential to ensure CE transition and utilise the technologies effectively for CE practices.

Health concerns were mentioned where emissions are released during production operations with additive manufacturing, meaning ventilation may be necessary while using the printers for product development [80], [88], [89]. In this regard, Kumar et al. [90] has constructed a framework for blockchain technologies to monitor the performance in additive manufacturing. This study provided limited information regarding the framework monitoring emissions impacting health, even though the performance considered age of employees and carbon emissions. Product designs may need to acknowledge safety and health aspects for waste monitoring [82]. Recycled plastics would also require sufficient quality for use in additive manufacturing markets [79].

3.4.4 Technological aspects

Technology performance for additive manufacturing can relate to the printer type and printing parameters [53], [81]. For instance, three different printers were analysed in the biomedical sector to compare the variations in the product's features [53]. Additive manufacturing should also be evaluated to acknowledge its impact on SC performance [64]. For example, Chiu and Lin [64] analysed additive manufacturing in a lamp production sector to determine its impact on SC flexibility. The study performed simulations to interpret scenarios with standard machines and additive manufacturing for product development and capacity was indicated as an essential aspect to balance the SC performance [64]. Benthos Buttons experienced quality variations and altered the production processes so that the printer develops product moulds, and injection moulding is used for manufacturing [79]. These aspects indicate that one may determine the required flexibility to utilise additive manufacturing for PWM and manufacturing. The level of flexibility is mentioned in one of the GSCF model's core processes for manufacturing [29]. SC designs could also relate to centralised or decentralised scenarios [53], [67], [69], [80]. For instance, the latter scenario implies that recycling facilities are nearer to waste sources than the former recycling scenario, meaning that the latter scenario can reduce energy requirements and emissions [91].

Open-source methodologies may assist in exchanging product designs yet companies must acknowledge IP, as well as privacy [39], [53], [71], [82]. IoT and blockchain applications may refer to these aspects for waste monitoring or participation in recycling [71], [82]. Information distribution concerns are categorised as a technological factor in this research due to the use of technologies and devices for information exchange [92]. Quality control is also included as a technological factor since this aspect relates to inspections, as well as to monitoring [80]. Quality assessments were analysed for distributed recycling but indicators may be needed to evaluate the waste for the operations from recycling to product development [68].

Organisations may also need to evaluate infrastructure and networks for applications [54], [82], [88]. Infrastructural aspects can imply recycling facilities to process materials for additive manufacturing [69], [79]. Koenig et al. [52] utilised the current hardware for IoT applications to evaluate tray conditions at airports. Energy may be needed for infrastructural requirements where organisations may consider alternative sources, such as solar, for additive manufacturing in PWM [88].

3.4.5 Environmental aspects

Environmental benefits of the applications include emissions in waste management, product life cycle extensions and waste reduction [54], [55], [73]. Energy has been evaluated in distributed recycling, as well as for additive manufacturing, blockchain and IoT [70], [72], [80], [82]. Malik et al. [80] mention that future research is needed regarding energy impacts for different materials in additive manufacturing. Environmental conditions must also be evaluated for these printers and plastic products [93].

Temperature is one of the environmental aspects impacting printing performance and plastic products' life cycle [88], [93]. Ultraviolet rays can also lead to degradation. These aspects may be essential to enhance recycling opportunities. Obydenkova et al. [65] suggest solar radiation as a possible environmental condition for further evaluation. Controlled environments may provide opportunities to control temperature differences during printing [88].

Bioplastics are used for distributed recycling and additive manufacturing in isolated areas [65], [68], [69]. These materials can assist in addressing the environmental impacts of conventional plastic during production operations [34]. However, bioplastics can also imply complications for waste sorting due to contamination in the waste flows, as well as new SCs to receive these materials for production [20], [34].

Factors are moreover susceptible to change over time [22]. A possible example identified in the SLR may relate to policies addressing information exchange and opportunities for innovation [54], [75].

3.4.6 Dynamic aspects

This research considers potential dynamic factors and impacts according to PESTLE. Distributed recycling and production, for instance, may assist in reducing environmental concerns compared to centralised recycling [91]. Open-source methodologies were evaluated for additive manufacturing and distributed recycling, and patents could be considered for the designs and information distribution [53], [69]. However, IP aspects may influence collaboration and information distribution for CE [75]. Governments could develop policies to address these concerns but the policies should also provide organisations with opportunities to implement the solutions [54], [75]. Furthermore, one must acknowledge environmental conditions, such as temperature differences, and emissions impacting health while using additive manufacturing for production [80], [88], [89], [93].

The research indicates Industry 4.0 impacts yet these studies focus on a particular technology, sector or country, providing limited information to generalise the factors for all applications and scenarios [55], [65], [67], [71], [90]. Koenig et al. [52] argue that IoT applications for maintenance could be approached in any industry. Nevertheless, this research encourages further analysis to ensure the factors can be generalised across different sectors.

Studies in the SLR consider different purposes for the applications, such as maintenance, product authenticity, and recycling improvement, as well as respective approaches for evaluation [39], [52], [79]. These applications then indicate the respective factors regarding implementation and potential improvements to address limitations. For instance, blockchain applications for tokenisation require further evaluation in other locations to confirm their effectiveness in recycling [71]. Chiu and Lin [64] performed simulations to determine the capacity for additive manufacturing in the lamp production sector. Paras et al. [55] evaluated case studies to acknowledge the processes and develop the model for clothing redesigning. Therefore, organisations are encouraged to evaluate their operations in terms of these factors and strategise accordingly for effective implementation. This aspect is also considered regarding the availability and applicability of Industry 4.0 applications.

3.5 Technology availability and applicability

Dijkstra et al. [20] state that the studies indicating the respective business models use various methodologies to address research questions. This research identified a similar aspect as the studies in the SLR consider different methodologies for the technology applications in PWM. Organisations may need to determine whether the technologies are relevant or available for adoption in terms of their respective operations and environment. Biomedical and reindeer husbandry industries, for instance, would need to acknowledge health and cultural aspects regarding additive manufacturing [53], [65].

Bioplastics may be adopted to address regulations, demand for sustainable products or littering considerations [20], [34]. Chemical recycling can assist in managing contaminated plastics; organisational culture is a possible consideration that may be needed to motivate change for technology adoption or integrate with stakeholders for sustainability [35], [36], [94].

The SLR has identified research including Industry 4.0 and one of the alternative solutions, such as bioplastics [65], [95]. Cruz Sanchez et al. [68] analysed literature on distributed recycling and acknowledged [96] to explain that chemical recycling could assist with contaminated plastics. Organisations may need to acknowledge essential considerations related to culture and change management for encouraging Industry 4.0 adoption in manufacturing to achieve sustainability [36]. Furthermore, training is required to motivate involvement and ensure the technologies can be utilised effectively [79], [84].

Table 4 provides an overview of the articles analysing Industry 4.0 technologies with respect to each factor as an extension of the Sankey diagram in Figure 4, as well as illustrating potential opportunities for the applications with respect to each factor. For example, potential opportunities for government involvement could imply monitoring the recycling operations for policy development [39]. These examples, however, do not reflect the count in the Sankey diagram as certain factors and opportunities are only identified after the themes have been finalised for the conceptual framework. The opportunity to use solar energy for additive manufacturing, for example, was not included in the count as this factor was identified after the themes have been finalised for framework development [88].

Table 4: An overview of factors with respective technology applications and opportunities

Factor	Industry 4.0 Technology	Potential Opportunities
Government involvement	Blockchain, IoT, additive manufacturing [39], [54], [72], [90]	Governments can use the technologies to monitor recycling performance and register stakeholders [39], [72].
Policies, regulations and standards	Additive manufacturing, IoT, blockchain and big data [39], [54], [68], [75], [77]	Regulations could assist in enhancing traceability and standards for quality evaluation in distributed recycling [68], [75].
Investments	Additive manufacturing, artificial intelligence, IoT and blockchain [52], [54], [65], [69], [73], [77]	Organisations may have challenges regarding investments for the solutions [54]. However, an opportunity could relate to the use of open-sourcing or current hardware to address expenses [52], [69]. This aspect requires further evaluation for confirmation.
Market aspects	Blockchain and additive manufacturing [68], [69], [71], [79], [83]	Distributing manufacturing could promote market growth for additive manufacturing and secondary plastics [69]. Marketing may also imply potential adoption diffusion for blockchain technologies [71].

Factor	Industry 4.0 Technology	Potential Opportunities
Stakeholder collaboration	Additive manufacturing, blockchain and IoT [39], [54], [86]	The technologies could assist in promoting collaboration for waste management improvement [39], [54].
Cultural and social values	Additive manufacturing, blockchain and IoT [39], [54], [65], [71]	Blockchain could provide tokens for participation in waste management and enhance recycling [71]. Organisational culture may also be a potential topic for Industry 4.0 adoption in PWM [36].
Safety and health	Additive manufacturing and IoT [80], [82], [88]	Ventilation may need to be evaluated for potential use in additive manufacturing [89].
Knowledge of technology, processes and materials	Additive manufacturing, blockchain, big data, IoT and artificial intelligence [39], [54], [55], [75], [79], [87]	Blockchain could assist in monitoring plastics and address obstacles regarding education and the lack of data for CE [54].
Technology design	Artificial intelligence, big data, IoT, blockchain and additive manufacturing [39], [53], [55], [71], [72], [75], [76], [80], [82]	Technology development can enhance monitoring capabilities [75]. Algorithms could be addressed to improve the blockchain's performance in recycling systems [72].
SC design	Additive manufacturing, artificial intelligence, IoT, blockchain and big data [64], [67], [69], [71], [80]	Centralised and decentralised scenarios, such as distributed recycling and manufacturing, as well as balancing the SC performance [64], [67], [91]
Information distribution	Additive manufacturing, blockchain, IoT and big data [71], [75], [80], [82]	Blockchain applications could assist in monitoring the plastic life cycle and exchange information for CE [54].
Infrastructure	Additive manufacturing, blockchain, IoT and big data [52], [54], [67], [82], [88]	Blockchain could monitor the plastic life cycle while considering waste management infrastructural challenges [54].

Factor	Industry 4.0 Technology	Potential Opportunities
Quality control	Additive manufacturing [53], [64], [68], [79], [80]	A combination of additive manufacturing with injection moulding could assist with quality control of the final product [79].
Decisions for materials and product design	Artificial intelligence, IoT, blockchain, additive manufacturing [53], [55], [71], [76], [82]	Product designs could be evaluated to include features for waste monitoring [71], [72], [82].
Energy usage	Additive manufacturing, blockchain and IoT [80], [82], [88], [90]	Solar energy can be considered as energy sources for additive manufacturing and distributed recycling [70], [88].
Environmental conditions	Additive manufacturing and IoT [65], [82], [93]	Acknowledgement of the environmental conditions on the plastic life cycle could assist to improve recycling [93].

The conceptual framework considers the identified factors as themes, as well as the plastic value chain and CE strategies for solution development [13], [76].

4 CONCEPTUAL FRAMEWORK

Figure 5 represents an overview of the conceptual framework for Industry 4.0 to enhance PWM and promote CE. The components include the themes discussed above, as well as solution upscaling, the holistic perception and CE objectives [11], [18], [76]. The GSCF model is acknowledged to discuss the conceptual framework and its components for Industry 4.0 applications in PWM improvement [29].

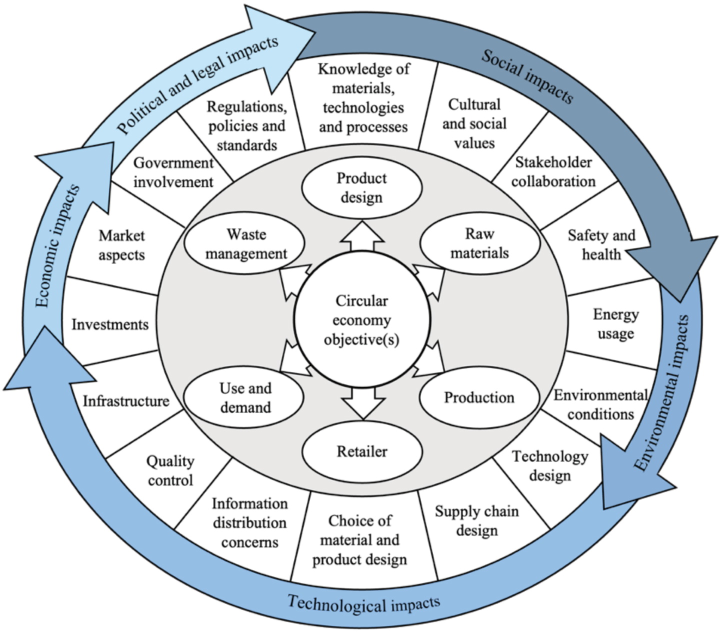

Figure 5: An overview of the conceptual framework for Industry 4.0 in PWM

4.1 Circular economy objectives and systematic perception

Levels in the GSCF model are identified as strategic, as well as operational considerations, for SC processes [29]. The former level plans each SC process while the latter level considers activities, such as determining metrics for performance evaluation. The conceptual framework addresses a similar aspect requiring organisations to find strategic solutions, using Industry 4.0 according to the CE objectives and respective adoption factors. Solutions are then analysed at the operational level for improvements and implementation. CE objectives are positioned in the center since clarity promotes alignment and individuals to be effective in decision-making, ensuring product delivery [97].

Organisations may begin the planning stage of the Industry 4.0 application by evaluating and selecting CE objectives throughout the plastic value chain for CE transition. The value chain in Figure 5 is an adapted version from Johansen et al. [13] and the objectives with arrows pointing at each phase indicating the systematic process, as well as the essence of waste hierarchies from Kirchherr et al. [18]. Organisations may plan for recycling, for instance, but the solutions must consider the overall objective to reduce waste and ensure a systematic approach for effective transition. Therefore, organisations can begin with recycling and take incremental steps to improve and upscale the solution for optimal sustainable performance and waste reduction [11], [31]. Organisations can also combine waste management strategies, such as recycling and reuse, to extend the product's life cycle [55].

Organisations can select any Industry 4.0 technology for the CE objective, such as IoT in maintenance strategies for waste reduction or additive manufacturing in a distributed recycling system [52], [68]. Companies can also select any position in the value chain or across the overall network for the technology application. For example, additive manufacturing can develop the products in the production phase using recycled plastics, whereas digitalisation and traceability may provide potential opportunities to enhance circular flows throughout the SC [75], [76], [79]. However, companies must understand the factors influencing technology adoption with respect to the selected CE objectives since SC designs rely on the chosen CE strategies [76]. This aspect is essential since the solution approach may indicate different concerns for the applications, such as material selection for additive manufacturing.

Decisions between bioplastics or recycled plastics may lead to different implications for recycling, such as infrastructural requirements to process recycled plastics and degrade bioplastics, as well as concerns for recycling performance since bioplastics can contaminate waste flows [26], [34]. Material decisions and product designs are included as technological aspects due to design attributes impacting recyclability and changes in production to use recycled plastics for product development [15], [34]. The themes in Figure 5 must be evaluated for the technology applications with respect to the overall value chain to ensure these solutions are effective for CE transition.

4.2 Factors and dynamic aspects

The GSCF model includes activities to plan the infrastructure, logistics and constraints for the flow management process in manufacturing [29]. These activities determine the manufacturing layout and operations with respect to the information from the other processes, such as product designs from product development, as well as possible metrics for measurement. The conceptual framework displays the themes for evaluation in each value chain phase to determine how the selected application could be implemented, as well as to enhance the systematic perception for potential requirements and impacts. For instance, additive manufacturing for production applications may need to consider environmental conditions impacting cooling rates and product degradation [88], [93]; legal requirements may involve certification; and technological aspects may furthermore relate to the product's quality due to the printing parameters [53], [81]. However, this framework is not strict in terms of factor classification and does not guarantee relationships between factors, aligning with research analysing factor interrelationships for Industry 4.0 adoption [33], [98].

Technological factors include material decisions yet this theme can also imply economic and environmental aspects, such as markets and environmental conditions, as indicated in the Sankey diagram in Figure 4 [69], [93]. The framework may indicate relationships between themes but cannot guarantee these relationships since factors depend on the location and sector [22]. The technology applications for PWM also imply different concerns, such as privacy for waste monitoring and recycling participation [71], [82]. Therefore, the framework cannot ensure how the themes would relate to each other for every application and industry sector due to the various considerations for solution development, as well as the need for further research on the applications and factors for all sectors.

Quality control is evaluated to understand why these themes must be interpreted throughout the value chain for the technology application. Distributed recycling, for example, requires measurements to determine the quality of the plastic during recycling and printing operations, which may refer to the melt flow index or investigations in the product's mechanical characteristics [68]. Quality is essential to ensure the plastics are sufficient for the printer market and that quality variations may need to be managed depending on the regulations for certain sectors [53], [79]. Companies may also need to determine how quality challenges could be addressed, such as combining the printers with injection moulding to standardise production. Therefore, the subcomponents for quality control relate to standards and inspections for organisations to perform their respective evaluations and determine applicable methodologies, potential solution adaptations and measurements for performance [53], [68], [80].

Organisations develop the solutions based on the evaluated themes and interpret the results for improvements. Arrows circulating the themes in Figure 5 indicate that these themes can also indicate potential dynamic aspects and impacts of the solution approach. For example, ventilation may be approached to address health concerns while using additive manufacturing during production [89]. Organisations are encouraged to assess the technology application's impacts according to each aspect, from economic to legal perceptions, to ensure the solution is effective and promotes scalability [32].

4.3 Upscaling

Upscaling is an enabler for CE transition [11]. The SLR has identified research performing simulations or pilot tests to assess the solution's performance [64], [71], [82]. For example, Chiu and Lin [64] conducted simulations to assess additive manufacturing impacts on the SC performance, acknowledging how capacity can affect SC flexibility.

One should note that if the organisation is planning to implement a solution on a small scale and then approach upscaling, the organisation must consider factors that could hinder upscaling, as mentioned in [32]. This aspect is considered since research is limited in its ability to generalise all the factors for the technology applications, meaning the themes require further investigation to ensure applicability for specific industries, as well as to identify potentially unidentified themes for evaluation. Nevertheless, organisations are encouraged to assess the themes in Figure 5 as a starting point for solution development and then assess the impacts to address limitations and promote scalability.

5 CONCLUSION

Plastics are identified in various products but a systematic perception of the overall value chain is essential for CE transition. Industry 4.0 technologies may be enablers for CE but factors for adoption vary between countries and industries. This research evaluated these technologies for PWM in SCs to construct a conceptual framework for solution development.

The framework acknowledges the CE objectives, plastic value chain and adoption factors to enhance the holistic perception for Industry 4.0 applications. Companies need to evaluate their operations to determine CE objectives, technology applications and associated factors for solution development. The solutions should then be assessed to acknowledge the impacts and opportunities for improvement, as well as to promote scalability. A case study will be performed in future research to refine the framework and determine which factors should be prioritised for solution development and evaluation.

Industry 4.0 technologies offer various opportunities to enhance plastic waste circulation for CE. Applications identified in the SLR are diverse but future research must ensure that the applications and respective factors can be generalised for each sector. Waste reduction and reuse should consider maintenance strategies and processes for product designs. Examples of these applications are also displayed according to the core processes in the GSCF model, indicating potential utility throughout the SC for PWM.

Solution alternatives that relate to bioplastics, organisational culture and chemical recycling may be used to address challenges such as littering, waste contamination and to motivate change. Nevertheless, these alternatives were not evaluated extensively compared to the technologies. Future research could investigate these alternatives for CE motivation.

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