Managing the Material Flow in Textile and Clothing Closed-loop Supply Chain with Product, Material, and Energy Recoveries: A Conceptual Framework

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Abstract. The emerging era of fast fashion has broadened the issue of sustainability and post-consumer waste in the textile and clothing industry. Textile and clothing manufacturers carry out Reverse Logistics (RL) and Closed-loop Supply Chain (CLSC) operations to manage waste related to used garment products. This study reviews existing literature on RL and CLSC in the textile and clothing industry and develops a conceptual framework for material management. This study proposes a framework to manage the flow of material in CLSC with three recovery alternatives, i.e. product, material, and energy recovery. We suggest a CLSC model involving a textile manufacturer, garment manufacturer, fashion retailer, and MRF (Material Recovery Facility). We propose an RL scheme with 100% recovery and no disposal activity. The proposed model allows the CLSC system to recover waste into energy and utilise it as an alternative energy in the upstream supply chain. We discuss some of the model limitations along with its challenges for implementation.

1 Introduction

Issues related to post-consumer waste have gained considerable attention in the global industry. For the last decade, reverse logistics (RL) and closed-loop supply chain (CLSC) have attracted many researchers as the two concepts aim to reduce post-consumer wastes, conserve resources, and extend the life cycle of products. The motivation for RL mainly comes from three main aspects: environmental legislation, customer awareness, and economic motivation [1]. RL practice enables the creation of a sustainable supply chain by reducing the use of natural resources and consuming less energy and pure raw materials [2]. The RL practices are common in many industries, such as automotive products, printers, photocopiers, refrigerators, air conditioners, washing machines, tires, and PCBs [3]. Many fashion companies, such as Zara, H&M, and UNIQLO, have also started implementing RL practices [4]–[8].

The textile and clothing (T&C) industry is a classic representation of the global supply chain. It significantly contributes to the global economy and international trade [9]. In countries like India, China and Indonesia, the T&C industry is one of the fastest-growing sectors. According to the Creative Economy Agency (Bekraf) in Indonesia, with a contribution of 18.01% and a GDP growth rate of 4.05%, the T&C industry has become the second-highest contributor to the creative economy.

However, unfortunately, the T&C industry has become one of the most significant global waste contributors. The industry ranks second as the largest waste producer in the world, right after the oil and gas industry. It is noted that 10% of global carbon emissions and almost 20% of global wastewater are generated by the T&C industry. It was reported that as of December 2018, the volume of the global fashion market was valued at US$1.7 trillion, and around 85% of garment products ended up in landfills [10].

The issue of consumer waste from T&C products is a significant concern for the global industry. The Extended Producer Responsibility (EPR) policy has forced producers to manage, minimise, and eliminate environmental waste [11]. Supply chain players have to motivate consumers to "return" unused items to reduce the amount of waste in landfills. Producers use various recovery techniques to give consumer waste a second life. For example, used clothing can undergo multiple recovery processes, such as reuse, recycling, refurbishing, and energy recovery [12].

The unused textile and clothing products are commonly called PCTW (Post Consumer Textile Waste). According to [13], PCTW refers to textile waste generated after the end consumer uses the product, which has been discarded or unused for several reasons, like being worn out, damaged or outgrown. The management of PCTW can be done using several options, including product, material, and energy/thermal recoveries [14]. Product recovery, generally through reuse and refurbishing, is the most common recovery option in the T&C industry. PCTW, which are still in good condition, are usually sold to the secondary market

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or donated through charity [15]. Material recovery is returning PCTW into material for production. The process is called material recycling. Clothing products such as jeans, jackets, and cotton-based clothing can be recycled into material, later used as a substitute for virgin material [16]. Material recycling reduces the use of pure material and is considered more economical and environmentally friendly [17].

In addition to product and material recoveries, PCTW can be recycled into sustainable energy by energy or thermal recovery [12]. The operation has been initiated by many recycling companies in Japan, Norway, China, and Portugal [12], [18]–[21]. According to [18], the energy potential of cotton briquette made from PCTW can save energy expenses by 80% (compared to fuel oil), 75% (compared to wood pellets), and 70% (compared to wood chips).

Generating renewable and sustainable energy from PCTW becomes a promising effort for the future as it fights the current crisis for energy and reduces waste from the environment [22]. Nunes et al. [18] investigated the economic and environmental benefits of using biomass as an energy alternative in the textile dyeing industry. The study suggested replacing heavy fuel oil with textile waste briquettes in the steam boiler. The textile waste briquettes unexpectedly provide the best return on investment due to the associated reduction of energy costs. Energy recovery should be prioritised as a promising avenue for further study [23].

Product Recovery Management of PCTW makes the material and waste management system in the T&C supply chain more complex. Technology for inspection and sorting activities, green technology for recycling and transportation, designing an optimal network for CLSC, managing inventory, and determining the optimal SC coordination are some challenges of implementing RL and CLSC [24]. Therefore, a framework for controlling the flow of materials in the T&C CLSC needs to be developed.

Based on the above discussion, we attempt to address two research questions:

1. How do materials move in the T&C CLSC system, which involves product, material, and energy recoveries?
2. What are the challenges to implementing CLSC in the T&C industry, which involves product, material, and energy recoveries?

This study develops a conceptual framework to manage the material flow in the T&C CLSC. We propose a closed-loop recycling system rather than an open-loop recycling system. We discuss some challenges of the proposed framework's practical implementation and potential developments to improve the sustainability of T&C CLSC.

2 Literature Review

2.1 Product Recovery Management (PRM)

Product Recovery Management (PRM) is commonly associated with RL and CLSC. PRM includes collection, recovery, re-distribution, and resale [25]. In addition, PRM usually involves controlled disposal activities through landfills for some used items that are not qualified to be recovered and resold to the market. PRM is defined as managing products, components, and materials from End-of-Life (EoL) items as a form of social and environmental responsibility from manufacturing companies [16]. Product recovery aims to reduce waste by recovering as much economic and ecological value as possible [16], [26]. In addition, product recovery is also motivated by increased profitability, social responsibility, legislation, increased market share, and brand protection [27]. PRM enables value re-creation of used products returned to the system [28]–[30].

According to [31], activities in PRM are divided into several stages, including 1.) used items collection, 2.) inspection and sorting, 3.) recovery process, and 4.) redistribution and reselling to customers. Meanwhile, the types of recovery processes can be divided into 1.) product recovery (such as repair, refurbishment, reuse, remanufacturing, and cannibalisation), 2.) material recovery (recycling), 3.) component recovery (remanufacturing), 4.) energy/thermal recovery [14], [16]. The type of recovery is determined based on product characteristics and available technology. Manufacturers may implement multiple types of recovery processes. For example, the combination of product, material, and energy recoveries carried out by multinational T&C companies to reduce the waste of clothing products in landfills [12], [20].

2.2 PRM in the Textile and Clothing Industry

According to [32], [33], T&C industrial waste can at least be classified into three categories, i.e. post-industrial waste, pre-consumer waste, and post-consumer waste. Post-industrial and pre-consumer wastes are classified as production waste, while post-consumer waste is End-of-Life (EoL) products, better known as PCTW (Post Consumer Textile Waste). Efforts to reduce the ecological impact of PCTW are considered to result in higher product prices. Thus, end customers tend to buy fewer clothes or extend their wearing time (slow fashion). This can reduce the company's profit margin [12]. Therefore, researchers have begun to propose solutions, including how to find a composition of fabrics that are more environmentally friendly to reduce the use of cotton, implementation of more advanced technology for sorting and remanufacturing, development of more efficient washing and drying processes, improve energy efficiency and the use of renewable energy throughout the life cycle of T&C products [34].

Used garment products with high quality are recovered through direct reuse. Generally, direct reuse is done through donations and charity programs, such as UNIQLO, which develops a sustainability program in collaboration with UNHCR (United Nations High Commissioner for Refugees) [35]. In addition, product recovery can also be carried out through a refurbishing process, in which used products are recovered to a certain quality level and then resold on the secondary market.

Used garment products can be recovered through a recycling process known as material recovery. Through the RE-UNIQLO program, UNIQLO Japan recycles 100% of the material for its ultra-light down jackets, down and feathers. The recycling process uses technology developed by UNIQLO with TORAY [35]. Apart from being processed into new garment products, recycled products can also be used as car insulation materials. UNIQLO processes about 22 units of T-shirts (weighing +4.3kg) into fibre and recycles them into soundproofing material for one car [35]. This material can reduce engine noise in petrol cars and high-frequency waves in electric cars.

Apart from product and material recovery, post-consumer T&C waste can be converted into energy. The process is called energy or thermal recovery. Fabric waste can be reprocessed into Refuse Paper and Plastic Fuel (RPF). RPF is an alternative to fossil fuels and can be utilised for industrial purposes such as boilers in the textile and paper industries. RPF is said to have better combustion characteristics than coal. With an equivalent calorific value, RPF is easier to handle and store and produces lower CO_2 emissions [36]. A Japanese textile trader and a resource recycling company, Itochu and Ecommit, carried out reuse, recycle, upcycle, and thermal recovery for T&C waste in its latest project, "Wear to Fashion" [19]. Fig. 1 shows the schematic diagram of the "Wear to Fashion" project by Itochu and Ecommit.

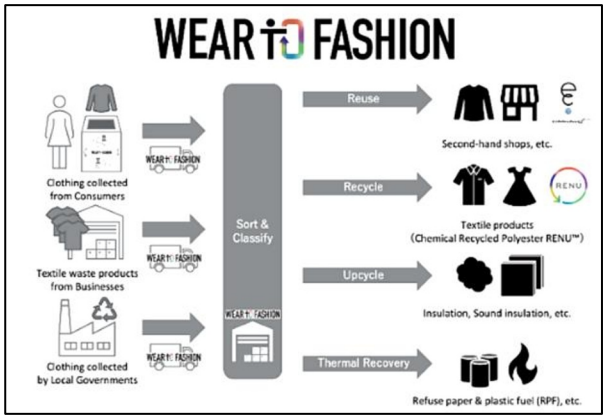

Fig. 1. The Reverse Logistics Operations Carried Out by Itochu and Ecommit [19]

2.3 Closed-loop Supply Chain of Textile and Clothing Industry

According to [37], the structure of T&C CLSC consisted of raw material suppliers, yarn manufacturers, fabric manufacturers, apparel manufacturers, and 3rd party collectors. In their study, they stated that collectors might include recyclers, remanufacturers, and repairers (Fig. 2).. In contrast, according to [38], T&C CLSC may consist of manufacturers, distributors, retailers, second-hand distributors, and second-hand retailers (Fig. 3). In Chengdu, China, closed-loop clothing recycling system involved fabric manufacturer, garment manufacturer, retailer, collection centre, sorting centre, and washing and recycling centre [7]. In France and Germany, the generalised T&C CLSC comprises fashion retailers and producers, collection points, sorting & recycling centres, and redistribution channels [39].

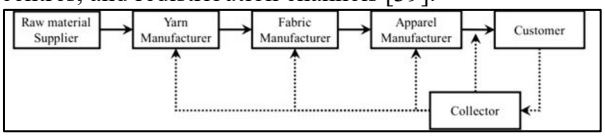

Fig. 2. CLSC Structure of T&C Industry in China [37]

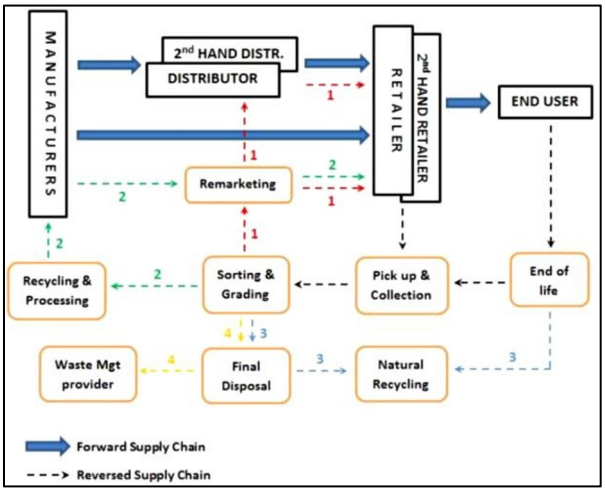

Fig. 3. Forward and Reverse Material Flow of T&C CLSC in Norway [40]

As seen in Fig. 3, the PRM activities for the end-of-life T&C products conducted by a fashion manufacturer in Norway include remarketing, recycling, and final waste disposal [40]. Meanwhile, in China, the recovery options for PCTW are generally recycling, remanufacturing, and repair [37]. Rotimi et al. [15] studied that the recovery options in the CLSC system for PCTW can be classified as reuse (repair, refurbishment, rental, etc) and recycling (e.g. upcycling, remanufacturing, and downcycling). To the best of the author's knowledge, the existing literature has not yet included energy/thermal recovery as one recovery option in the closed-loop recycling system of the T&C industry. Energy/thermal recovery is one of the recovery options that has been carried out by many companies in developed countries such as Japan, Norway, China, and Portugal [12], [18]–[21]. Moreover, it is considered a promising effort for the future of the T&C industry [23].

2.4 Energy or Thermal Recovery from PCTW

As discussed earlier, PCTW can be converted into sustainable energy such as Refuse Paper and Plastic Fuel (RPF). RPF is an alternative to fossil fuel and can be utilised for industrial purposes such as boilers in the textile and paper industries. RPF is superior to coal because it is easier to handle and store with an equivalent calorific value and is more environmentally friendly because it produces lower CO_2 emissions [36].

Referring to [12], cotton has a high cellulose content (85-95% dry weight). Therefore, this material can be converted into biofuels. In addition, one of the solvents used in the pretreatment process for the cotton/polyester mixture, namely N-methyl morpholine-N-oxide (NMMO), produces methane gas. It is known that using NMMO in the pretreatment process for jeans products

made from 100% cotton can have 400 ml of methane/g volatile solids/day. NMMO is very beneficial because it requires less energy, is easy to operate, is environmentally friendly, and reusable.

Furthermore, because the thermal processing of PCTW does not involve separation or sorting, it can also produce heat energy in a relatively simple process. For example, a combined heat and power plant (CHP) using fluidised bed combustion technology generates energy in Sweden. Combustion of textile waste mixed with cardboard provides optimal results and more uniform combustion [41].

Roushan [42] studied textile and garment waste as an energy source for boilers with an incineration process. The study revealed that installing Jhut boilers fuelled by textile and garment waste has been proven to reduce boiler operational costs, minimise consumption of natural resources, and reduce the amount of fabric waste.

According to [18], recovering energy for a given quantity of PCTW, compared to disposal to landfill, has several advantages, including:

1. Recovering PCTW into energy eliminates costs related to landfill disposal,
2. More sustainable to the environment by no longer sending low-density, high-volume waste of PCTW to landfills,
3. More economical and environmentally sustainable when combined with other fuels to produce energy,
4. Lowers operating expenses by reducing the cost of transportation and storage before being disposed of in a landfill.

Implementing energy recovery as an integrated option for recycling PCTW is more profitable for the supply chain. The alternative energy converted from PCTW, in the form of cotton briquettes (see Fig. 4), can be utilised in the upstream supply chain, such as boilers in textile manufacturers. As studied by [18], using cotton briquettes from PCTW in the textile industry provides superior economic and environmental benefits compared to fuel oil, wood chips, and wood pellets. Energy recovery enables closed-loop recycling in the T&C supply chain. Manufacturers and recyclers have a great economic opportunity with the implementation of closed-loop recycling [43].

Fig. 4. Cotton-based Briquettes Made Up of 90% Cotton and 10% Polyester [18]

2.5 Challenges for Reverse Logistics

Applying RL and CLSC is close to achieving sustainability and circular economy. Nevertheless, since RL and CLSC require and involve significant financial outlays, ensuring their efficient execution is challenging. The costs of collecting, transportation, inspection and sorting, and recycling are associated with RL and PRM activities. Of the four expenses, the most significant share goes toward transportation, making up about 50–60% of the total. These transportation costs include vehicle investment, driver wages, fuel costs, and machine maintenance, to name a few [37].

The cost of recycling directly affects the price of recycled material. In the T&C industry, the price of regenerated recycled fibre can be up to 30% higher than that of virgin fibre. Therefore, textile recycling is typically carried out in most countries to reduce the price of recycled fibre in exchange for a donation. To reduce the cost of the entire PRM process, companies can implement a strategic alliance and coordination within the supply chain, which includes retailers, third-party collectors, recycling centres, manufacturers, and suppliers [6].

Okafor et al. [12] state that closing the loop in the T&C industry is challenging due to several factors, including a.) behaviour, education, and consumer care, b.) the lack of technical knowledge in the PCTW management process, including how to efficiently collect and sort textiles based on fibre type, and the lack of proper planning, c.) poor recycling technology and high recovery costs, and d.) the increased complexity of logistics and inventory management in the CLSC.

The high degree of uncertainty around the quantity and quality of product returns, transportation, sorting, and difficulty in inventory and production planning and management are some of the barriers companies face to carrying out RL and CLSC [30]. Companies involved in CLSC must collaborate effectively, including planning and managing inventory, improving communication and coordination, and developing technology.

Organisations must ensure that RL and CLSC are carried out effectively so their benefits outweigh the drawbacks. Energy is required for the recycling and remanufacturing of waste/used items. Reverse supply chains transport waste and unused products back to the production facility and produce emissions. On the other hand, removing PCTW from landfills and utilising less virgin raw materials to create new products reduces emissions. Therefore, an economic and environmental analysis must be done to ensure optimal management of RL and CLSC.

3 Results and Discussion

3.1 The Proposed Framework for Material Management in CLSC

Based on the discussion in the previous section, we propose a framework for managing material flows in the CLSC of the T&C industry. Generally, the T&C supply chain consists of at least four channels, i.e. textile

producers, apparel manufacturers, fashion retailers, and material recovery facilities. In this case, the retailer commonly acts as a collector of used items from end consumers. Meanwhile, the Material Recovery Facility (MRF) organisation carries out the recycling facility used apparel.

In the proposed framework, we develop a closed-loop recycling system integrating three recovery options, i.e. product, material, and energy recoveries. Product recovery is carried out through the refurbishment of used products. In the refurbishment process, minor defect/damage is repaired, and the refurbished products are sold in the secondary market at a lower price [16]. Used items with moderate quality levels will undergo a recycling process. The recycled material will be returned to the textile or garment manufacturer as a substitute for virgin raw materials. The last recovery option is energy recovery. Energy recovery converts used items with the lowest quality level into sustainable energy in the form of RPF or cotton briquettes. The generated power will be returned to the textile manufacturers to be utilised as boiler fuel as an alternative to coal, wood pellets, and fuel oil. The proposed framework of materials management in the T&C CLSC is depicted in Fig. 5.

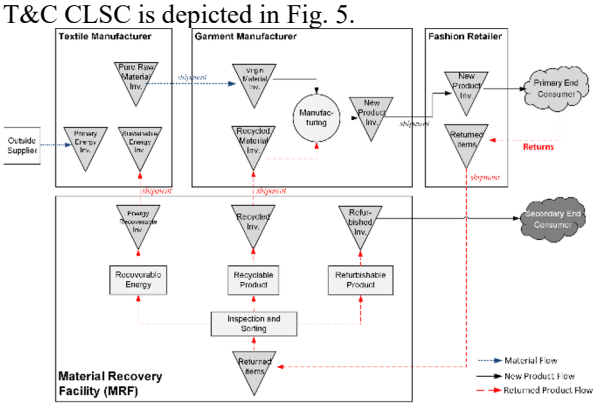

Fig. 5. The Proposed Conceptual Framework to Manage the Material Flow in T&C CLSC

As shown in Fig. 5, the material flows of forward and reverse logistics are managed within the CLSC system. The reverse flow of used garment products starts with the collection process, inspection and sorting, and recovery process. The collected used items are inspected and sorted based on their remaining quality. Garment products with only minor defects/damages can be processed into refurbishments. The refurbishment takes place in the MRF channel. In this case, MRF can sell the refurbished products directly. However, MRF can cooperate with another channel, such as a second-hand retailing company, to sell and distribute the refurbished products.

Used garments of moderate quality can be recycled into the material and used in manufacturing to produce new products. The recycled materials can be in the form of recycled fibres, recycled cotton, or recycled downs, which are used as insulation material for new garment products, e.g. light-down jackets. Therefore, the recycled materials will be returned to the textile and garment manufacturers.

In addition, the lowest quality of used products will undergo a downcycling process called energy recovery. The energy recovery process will convert the used products, such as RPF and cotton briquettes, into sustainable energy. It will be delivered to the textile manufacturer to produce energy in the boiler engines.

T&C factories power their machines using fossil fuels, including coal and natural gas [44]. Countries with large manufacturing industries, such as China, India, and Indonesia, rely significantly on coal as a primary energy source. Consequently, these nations carry substantial carbon footprints associated with their production activities [45]. In the proposed framework, using sustainable energy from textile waste becomes an energy substitute for primary energy sources. However, the limited supply of post-consumer waste from T&C products is one challenge in generating sustainable energy. Consequently, the potential energy generated may only be sufficient to meet a small portion of the overall energy demand in textile processing operations, including weaving, spinning, and chemical processing. Another option would involve purchasing energy from outside suppliers when sustainable energy produced from textile waste is insufficient to meet energy demands. Fig. 5 illustrates two distinct energy sources within the textile manufacturing facility: sustainable energy derived from the Material Recovery Facility (MRF) and externally purchased energy from outside suppliers. Energy supply and demand planning needs to be conducted by the CLSC system to ensure the availability of energy sources, both primary and sustainable energy, for the operations of manufacturing processes.

3.2 Discussion for Practical Implementation and Future Challenges

As discussed earlier, this study developed a framework to manage the flow of material and waste in the CLSC of the T&C industry. The proposed framework enables the implementation of a closed-loop recycling system where all the used items are 100% going to recovery, resulting in no disposal activity in landfills. We can eliminate waste and emissions generated through landfills and return 100% of the value from PCTW. However, the proposed framework has several limitations, including:

- Emissions will rise with the increased transportation activity and the recycling of used items back into the system. The use of green vehicles and an optimal CLSC network design are required for the implementation of the proposed framework.
- The sustainable energy generated from the energy recovery process enables the application of green manufacturing. The proposed framework may be suitable for countries with limited alternative energy sources.
- Integration of the three recovery processes is complex. It needs a set of reliable equipment and technology. The recovery facility needs to invest more in recycling technologies and human labour since there isn't enough technology currently available to help with the mixed fibre separation process [46].

- Textile and garment manufacturers are required to design recyclable and sustainable fibre and clothing. A product life cycle analysis must be conducted at the product design stage to implement RL and CLSC effectively.
- The proposed framework calls for improved SC planning and channel coordination. Retailers would have to set policies regarding how, when, and under what circumstances used products are being returned. The optimal coordination mechanisms, such as buy-back, profit-sharing, revenue-sharing, and other possible coordination mechanisms, need further evaluation.
- The heterogeneous quality of product returns makes it difficult for the recovery facility to inspect and grade the used products. The probability of an inspection error may also increase with the complexity of the inspection process. Therefore, used products must be inspected, sorted, and graded using reliable technologies and standardised procedures.
- Regulation concerning reverse logistics operations of PCTW might become a challenge for implementing the proposed framework. To protect local clothing producers and prevent the entry of unsuitable second-hand clothes, many developing countries, including Indonesia, have banned the importation of used clothes from overseas. However, rather than 'direct reuse,' this study offers an approach in which used clothing is sorted and recovered through refurbishing. In addition, reselling refurbished clothing must be done with the brand owner's consent. A specific contract may be applied, such as removing the brand tag to maintain the primary market for the product.
- One of the main issues facing RL and CLSC is the uncertainty within the quantity of product returns [6]. Improved inventory planning and management are necessary to ensure material availability and optimise production planning in the CLSC system. The objective is to reduce the entire RL and CLSC system costs.

4 Conclusions

This study develops a conceptual framework to manage the flow of material within the closed-loop supply chain of the textile and clothing industry. As mentioned earlier, we seek to answer two research questions. Here are the answers to the two research questions:

1. The T&C CLSC system involves at least three different kinds of material movement, including the flow of raw materials, new products, and returned products. T&C products have specific characteristics that make it feasible to recover used items using various options. The developed framework has incorporated the integration of product, material, and energy recovery and enables the creating of a closed-loop recycling system with 100% value recreation and no disposal. Using the developed framework, post-consumer waste from the T&C sector can be utilised as sustainable energy in the upstream supply chain.
2. Several limitations and challenges for the proposed CLSC framework include the increase in emissions for transportation and recycling activity, development of technologies for inspection, sorting, and recycling process, optimal inventory planning and management, improved supply chain network and coordination, regulations, and uncertainties of quantity and quality of product returns.

The proposed theoretical framework would be suitable for countries with limited alternative energy. Additionally, countries like the European Union, India, Australia, Japan, Canada, and the United States [47], which have rigorous regulations concerning EPR, sustainability, and carbon emission, may be appropriate to implement the proposed framework. Applying the developed framework for global supply chain networks involving many countries requires further study and analysis. Design for an optimal CLSC network is necessary to ensure that the implementation of the proposed framework can run efficiently. Future research may be conducted in these areas of study.

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