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Review of Recycling Processes with Respect to Carbon Emission and Waste Management

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***Abstract*:**

An efficient recycling process has been identified as the vehicle that drives an effective green supply chain management, resulting in the reduction of waste in the manufacturing supply chain. This study offers an overview of the different stages and structures of recycling with respect to carbon footprint analysis and waste management through an extensive literature review. Various internet-based search engines were used to uncover the literature. The review found that research and practices in recycling have covered almost all aspects of recycling such as the collection of end-of-life products, their processing, recycling and subsequent integration of the recyclables in manufacturing, remanufacturing, and waste disposal. Special focus was given to prospects and opportunities for further research. On that ground, various aspects of the recycling processes were identified and highlighted to further enhance research in the field of recycling.

Keywords: *Recycling, Carbon footprint, Waste management, End-of-life Products, Remanufacturing.*

I. INTRODUCTION

Owing to the rapid increase in Greenhouse Gas (GHG) emission in recent years, more attention has been given to the protection of the manufacturing ecosystem. Studies have shown that manufacturing companies are the major contributors of GHG emissions as they are directly involved in using raw materials to generate products and services as well as the disposal of the end-of-life (EOL) products. The management of EOL products is now one of the main concerns in many countries around the world. Recycling involves activities connected with the management of EOL products as well as the treatment of tools, products, mechanism, and resources or even complete recuperation of technological systems which can be applied for proper EOL product management. More specifically, recycling is the approach of transferring goods from their normal end-of-life stage to value extraction and/or proper disposal.

In recent years, "carbon footprint" has been in the limelight under the consideration of ecosystem protection. Awareness of carbon footprint impacts and its measurement has shown a rising trend across various industries. An organized explanation of carbon emission was presented [1] as the measure of the total amount of carbon dioxide (CO_2) emission that is directly and indirectly caused by an activity or is accumulated over the life stages of a product [1]. From the description, it can be understood why it is necessary to give attention to both direct and indirect carbon emissions. The carbon footprint caused by the operations of manufacturing units goes under direct CO_2 emission while extended suppliers and customers comes under the consideration of indirect CO_2 emission. Carbon footprint study has shifted from the coverage on direct impacts of CO_2 emission that is those from on-site processes towards the exposure of indirect impacts of CO_2 emission in the total product supply chain.

Achieving potential value from used products has been attracting the interest of researchers and practitioners in recycling. Recycling focuses on the management of EOL products through recycling of the materials as well as product recovery through remanufacturing. Over the past three decades, researches on recycling have been mainly focused on recycling approaches. Some of the research emphasis on recycling systems includes production planning and ecological issues with case studies and optimisation of network design [2], distribution planning, production planning, and inventory control [3].

A number of quantitative models were also proposed for recycling system, such as the model that minimises the cost of multi-time-step and multi-type hazardous waste. In addition, some researchers looked at the interfaces between supply chain and sustainability through product design, product life addition, and product repossession at EOL [4]. Furthermore, others investigated sustainable marketing and green market development for recycling [5]. Meanwhile, recently has been proposed a recycling model based on carbon footprint [6]. Mixed integer linear model was adopted to make the carbon footprint constant in every location like recycling centers and disposal centers.

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Integrating carbon footprint in different stages of recycling has become an important strategic issue. Carbon footprint integration in recycling is aimed at increasing environmental performance, thereby improving corporate sustainability and competitiveness.

The review paper has been extended to study important structures of recycling such as product procurement, collecting of used products, network construction, pricing of recycling, and joining activity along with environmental footprints such as carbon footprint in reverse supply chain, as it is the core to help the company to stand out in the market and become more profitable.

Carbon is observed as a major contributor in GHG. Therefore, it has attracted the attention of researchers to measure the carbon footprint in the different stages of recycling. Moreover, focus has been given to the scopes of the studies of carbon footprint in recycling or reverse supply chain to mitigate the challenges of global climate change and minimize the amount of GHG emission.

II. Materials and Methods

In order to establish the extent of researches that have been conducted in recycling, content analysis and observation approach were adopted to review the literature. All forms of recorded contents were systematically assessed in the content analysis process. Content analysis has been identified as an efficient method in the review process. All forms of recorded communications have been scientifically evaluated by using content analysis method. This technique serves to build up research opportunities by distinguishing the literature into several categories.

Byrd and Davidson [7] adopted content analysis method in order to investigate the association of information technology with inventory network. Holdford [8] also used content analysis to introduce the methodology of content analysis in the field of pharmacy advertising and highlight major ideas and problems. Content analysis was also used to conduct a review on third party logistics [9].

The literature was gathered from various electronic sources. In addition, different published literature and books were covered in the acquisition of the literature. For the review of the electronic sources, search engines were utilized to survey the literature from Science Direct, Google Scholar, Springer Link, Ingenta Connect, INSEAD, Hindawi, and a host of other electronic sources. Various keywords were used to search the literature such as closed loop, carbon footprint, recycling, sustainability, remanufacturing, green supply chain, product returns, footprint analysis, and recycling.

Business logistics, optimization of logistics network, production and operation management, and logistics management are some of the categories that originated from the journals. The review was extended to sustainable development by covering the aspect of carbon footprint. For the assessment of sustainability and its modules, footprint has been used in recent years and it can be categorised into several areas like environmental footprints, social footprints, and economic footprints. Measurement of carbon footprint was performed and given significance in supply chain design phase [10]. Researchers also considered the carbon footprint in the context of supply chain of automotive industry [11]. In the same case study Lee viewed carbon footprints' direct and indirect impact on supply chain, as clearly shown in Figure 1.

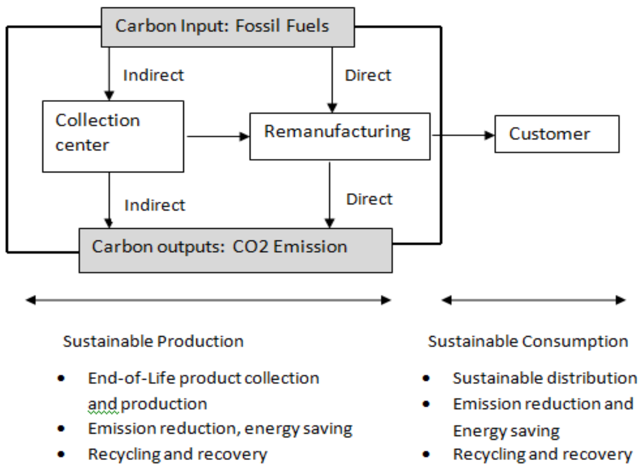

Figure 1. Direct vs. indirect possessions of carbon emissions in reverse supply chain [adopted from i-Hoon Li, 2011]

A clear classification is very much needed to measure carbon emission and footprint. In the Figure, direct and indirect carbon emissions across the reverse supply chain have been identified. Major footprint analysis in recycling can improve the sustainable development in various structures or stages of recycling. Hence, this review is conducted on the different aspects of recycling where carbon footprint related analysis can be applied using the content analysis method.

III. Results and Discussion

Recycling was first defined by The Council of Logistics Management (CLM) in 1992 [12] as the application of logistics in recycling, waste disposal, and management of hazardous materials; a broader perspective includes all that related to logistics activities carried out in source reduction, recycling, substitution, reuse of materials, and disposal. In the same year, Pohlen and Farris (1992) gave a definition of recycling based on the role of logistics and led by marketing principles, as being "the movement of goods from a consumer towards a producer in a channel of distribution". In the late nineties, recycling was defined by including the processes and goals that involve in it [13]. The definition was "the process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods, and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal." Recycling has been adopted by many manufacturing industries to recycle the EOL products as a component of closed loop supply chain (CLSC). Reverse logistics is a process of returning EOL products for the purpose of remanufacturing [14]. For better understanding of recycling, comprehensive differences between forward and reverse logistics need to be

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identified first. Tibben-Lembke and Rogers [15] distinguished between forward and reverse logistics, the authors described recycling as an opposite flow of material or product to generate value or for proper disposal. When disposal is considered, then it may be considered the opposite flow of both product and packaging. Further, Fleischmann developed a framework to describe the difference in distribution between the forward and the backward logistics as shown in Figure 2.

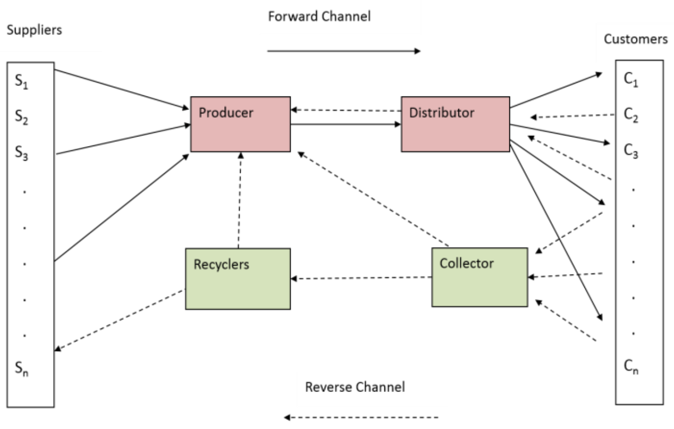

Figure 2. Framework of reverse distribution [Adopted from Fleischmann et al. 1997]

Recycling is an environmentally friendly attempt, which is capable of providing competitive edge to manufacturing companies in economic capacity. Environmental footprint calculation can swell the opportunity for sustainability in the recycling process. In recent years, environmental footprint is being used for the calculation of sustainability. Among the footprints, carbon footprint was first defined as the quantifiable measurement that recounts the generation of carbon by human [16]. As such, the activities that directly (internal, on-site) or indirectly (off-site, external, upstream, and downstream) emit CO_2 during the life stages of a product is evaluated to yield the total amount of carbon footprint [1].

In this paper, the review is extended to various structures of recycling to explore the opportunity to apply carbon footprint technique. Measurement of carbon footprint through the reverse supply chain is necessary to better comprehend, compute, and thoroughly investigate the effect of carbon emissions in total chain network.

A review of recycling shows that most articles related to recycling started gaining a lot of attention in 2005 [17]. There is much to be covered in the field of research of recycling in the context of carbon footprint-based analysis. Figure 3 shows the relevant studies on recycling with respect to the time frames derived from the abovementioned review.

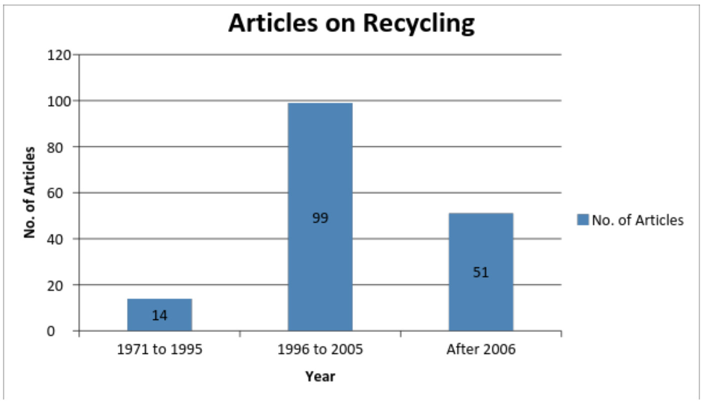

Figure 3. Number of articles published on recycling in different time frames

One of the main objectives of recycling is the collection of the EOL products for remanufacturing, recycling or proper disposal. The exact stages in this conversion vary from case to case [18]. This review discusses the structures of recycling and their areas of concern with the prospect of evaluating carbon footprint within the same precinct.

i. Take-Back and Collection

Collection means all of the actions that take place from the transportation of worn products obtainable to assembling them at any point where additional process is undertaken. One of the biggest challenges of recycling is the selection of the path in returning of the EOL product. Formalisation of the route can be both environmentally friendly and cost effective [19]. Most of the time firms select a common place for inventory of the EOL products that have been collected from the customers or end users. Scrutiny is performed to segregate the products based on their condition and composition. Decision need to be made whether the used products are going to be reused, repaired, refurbished, or remanufactured. The return or take-back process can be of the following three types: [12].

a) Manufacturing return: Components or products that have been recovered in the production phase are categorized under manufacturing return. For example, quality control return is part of manufacturing return. In addition to quality defect, manufacturing return may occur due to various reasons such as left-over raw material and left over final product during manufacturing. Manufacturing return has very little contribution to the total process of recycling in terms of vehicle transportation, inventory, and distribution. The critical part is to find out actual carbon cost and/or emission under this particular kind of return.

b) Distribution return: Refers to all the returns that occur in supply chain process during distribution of the product. For example, stock adjustment is a type of distribution return. Logistic support like inventory and transport planning is required to achieve proper collection method for such type of return, which also has deep influence on the carbon footprints.

c) Customer/user return: This is the kind of return which is initiated by the customer. Customer can return either in use or EOL product. A warranty return is a good example of this

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type of return. In certain cases, the manufacturer collects the product after the end of its life from the customer, which in turn increases carbon cost and emission of the company.

The return inputs of recycling are derived from new, used, and recycled materials. Collecting approaches for EOL product mostly depend on accurate set up of collection points. The consideration of collection points basically deals with the collecting actions and optimum network design for returned goods [20], [21], [22]. Product take-back strategies will result in maximum profit that can be achieved by implementing proper collection strategies for the EOL products [14]. Another research developed a model where a third party is engaged for the collection of products for recycling [23]. Authors also proposed a smart incentive plan for the users for disposing the used product at the desired place [24]. Some authors established a lower cost, improved recovery process through retail outlets shared with the regaining modules [25]. Difficulties emerging in collecting or take-back have been identified by many authors. Problems like locations of the collecting points as well as in combining of retail with outsourcing activities of recycling have also been highlighted [26]. In addition, research has been conducted on the collection of EOL product for recycling on the basis of carbon footprint. Product takeback is highly related to transportation approach of reverse supply chain and carbon emission. New vehicles introduction in the chain can improve the fuel efficiency as well as lower the carbon emission [27]. Many authors have drawn attention on the greening of transportation or logistic activities by the use of operation research methods and fuzzy mathematics [28-30]. Some of the literatures related to EOL product take-back or collection are shown in Table 1.

Table 1
Literature on recycling take-back and collection

Content	Literature
Collection	Wu and Dunn [31], Sarkis [32], Richey et al [33], Håkan Aronsson and Brodin [34], Karakayali et al [35], Frota Neto et al [36], Kohn and Brodin [37], Sundarakani et al [10]
Return	Barros et al [38], Brito et al [12], Min et al [39], Alshamrani et al [19], Qin and Ji [40]

ii. Recycling Structure

The structure of recycling refers to the network system, allocation of collection points, the system developed for the supply chain, integration of processes, and the control over them. Most of the authors paid particular attention on developing the network system for recycling as well as designing the strategic plan. Some of the authors looked at the design of the recycling network [41-44]. Other researchers looked at a different approach in designing recycling by building a recycling model that can calculate the collection cost predicatively [45]. In addition, a study has also reviewed the ideas about the characteristics of product recovery network with link to carbon emission [18]. Researchers developed an environmentally friendly and greater economic payback network design for recycling which opened up opportunities for the study of carbon footprint analysis in recycling network design [46].

Inspection and amalgamation are other important aspects of the recycling structure which have also been researched upon. Inspection covers all types of operations which identify whether the collected products are usable or not, and if so, in what way. Some researchers have looked at third party outsourcing for collection of EOL products to the inspection location [47] in a way that it becomes more the manufacturer's' responsibility than the consumers. This is consequent to governmental legislation on EOL products in many countries. Other studies looked at the global aspect and regulations of collected EOL products as well as their management [48]. Some other authors combined the demand and inventory policy of recycled and newly purchased products [49]. Similarly, authors have integrated the collection processes of reusable products with the selling of new products or forward logistics to simplify the inspection process.

Integrating manufacturing and remanufacturing processes is always a point of interest to researchers in studying the recycling structure. Furthermore, researchers have looked at the rearrangement of manufacturing processes to make the integration of manufacturing and remanufacturing operations a valuable option for recycling. Rearrangement is required in the manufacturing procedures, information system, and management of EOL products to achieve the integration of manufacturing and remanufacturing operations [50], [51]. In addition, the costs associated with the integration of manufacturing and remanufacturing processes have been looked at [52]. Other studies integrated the supply chain function with third party logistics providers and observed that the addition of third-party logistics suppliers can elevate supply chain management to a higher degree [53]. Many other researchers paid attention to the mechanism of inventory [54], product take-back [55], product design, and supply chain incentive [24] for integrated system. Some research provided a framework for integrated supply chain or closed loop supply chain with concern on a single type of footprint that is carbon footprint [56]. Furthermore, some commonly used approaches and methodologies applied in environmental footprint criteria for the manufacturing and remanufacturing units have been identified [57]. The grouping of literature related to recycling structures is provided in Table 2.

Table 2
Literature on recycling structures

Content	Literature
Inspection and consolidation	Murphy and Poist [58], Galbreth and Blackburn [59], Ahluwalia and Nema [60], Webster and Mitra [61], Tagaras and Zikopoulos [62], Ferguson et al [63], Galbreth and Blackburn [64], Teunter and Flapper

	[65]
Integrating manufacturing	Wells and Seitz [66], Chouinard et al [50], Schultmann et al [67], Kocabasoglu et al [68], Fuente et al [51], Fuente et al [69]

iii. Recycling Processes

The process of recycling covers the areas of remanufacturing, refurbishing, disassembly, inventory mechanism, reverse supply chain planning, after sales service, and waste disposal. Remanufacturing is a procedure of transforming used products into new usable products. Again, considering the reverse supply chain, this is vastly different from the forward supply chain [70]. The number of reprocessed products, cost, time, quality, and demand makes is uncontrollable compared to forward logistics. It is not always as symmetric as forward logistics [3]. There are many difficulties in recycling like unclear destination, many users to one collection centre, transportation, disposition is not clear, more difficult forecasting, less transparent process visibility, complicated marketing, and other product quality issues. Content analysis helps to understand the scopes of carbon footprint-based studies in the critical areas of recycling processes.
Energy utilization during warehousing is a major concern to the environment. There is an indirect CO_2 emission during production and utilization of energy. Air conditioning or heating as well as material handling operations and lighting are some of the operations that are performed within the inventory management by manufacturing industries which require electrical power to function [71]. A study designed an inventory model for returned products considering the seasonal and lifetime factor of the products [54]. Inventory management aspect of recycling is the most crucial area for consideration in sustainability or environmental study. Researchers have found this area as a very interesting field of study as it has played an important role in footprint or carbon footprint related studies. Some authors also looked at carbon footprint at the inventory level [72] by managing optimum order level and examining the carbon impacts such as carbon cap, carbon trade, and carbon price. Others considered from a standard economic order quantity model to a multi-echelon order quantity by Pareto analysis to optimise the carbon footprint in inventory management [73]. The literatures associated with recycling processes are listed in Table 3.

Table 3
Literature on recycling processes

Content	Literature
Inventory	Inderfurth et al [74], Vlachos and Dekker [75], Hwang et al [76], Oh and Hwang [77] (2006), Zhou et al [78], Vercraene and Gayon [79]
Supply Chain	Choi et al [80], Bakal and Akcali [81], Debo et al [82], Kim et al [83], Reimer et al [84], Tang and Teunter [85], Hu and Xu [86]

One of the major focuses of researchers under the recycling process is reverse supply chain. Many authors have researched on the different modules and planning factors of reverse supply chain but only very few have focused on the footprint analysis in the same field [83]. Some authors focused on the planning and control of remanufacturing [87] in which optimum planning was identified to reduce carbon emission in the remanufacturing process.

iv. Recycling Output

Recycling output refers to the forwarding of reusable goods and/or recyclables to a prospective marketplace and the management of moving them to the imminent consumers. It not only helps to increase the product life cycle but also retains customers through improved service. Customer retention and relation can be achieved in recycling through improvised return policies and greater customer relationship is beneficiary to the recycling environment [88]. It directly helps to create sustainability in supply chain which has positive impact on social, environment, and economic activity or triple bottom line of sustainability. Authors also acknowledged green logistics approach in recycling by giving emphasis on the hazardous output or waste management by keeping the logistics management environment friendly [89]. A supply chain network model to assess the impact of ecological issues on transportation approach has been developed [90]. The model was designed in a way to reduce the CO_2 emission in the transportation. In a recent research, a new carbon emission constraint has been developed where carbon emission is limited to per product delivery [91]. Groups of literature under recycling outputs are specified in Table 4.

Table 4
Literature on recycling output

Content	Literature
Customer Relation	Wise and Baumgartner [92], Daugherty et al [93], Sarkis et al [94], Daugherty et al [95], Srivastava [42]
Product pricing and competition	Sahay et al [96], Ferguson and Toktay [97], Ferrer and Swaminathan [98], Vadde et al [99]

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IV. Future Research Opportunities

Environmental initiatives

Recycling provides an enormous opportunity in the field of research and yet very little attempts have been made to explore this opportunity. From the review of recycling, four basic structures in recycling were identified. In this research, the different segmentations applied under the basic four components have been looked at. From this point of view, identification of environmental initiatives for each component of recycling can be a core area of research. Environmental Performance Index (EPI) computation can be applied at each stage of recycling. In order to identify the effects of environmental initiatives, it is necessary to compare those initiatives with respect to the recycling activities of a particular company or industry. Another interesting area of research is to measure EPI of recycling for an industry by benchmarking the environmental performance for that particular industry.

Economic initiatives

Most of the research conducted has focused on recycling structures and yet, many findings cannot be empirically applied. Bi-objective or multi-objective mathematical or differential programming can be applied in order to optimize the different combinations of recycling networks. Environmental and economic aspects of recycling are great areas of research with regards to the study of all the recycling links. Many authors have done various works on transportation and cost minimization for forward supply chain but this combination can also be investigated for recycling.

Different objectives could also be combined with such research such as transportation and demand for the remanufactured product or demand for product and cost. Multi-objective integer programming for multi-echelon recycling network design can be a great area of research.

In addition, the social characteristics of recycling can be combined with economic and ecological features. Multi-objective optimization programming for recycling should also be applied in different industries like automotive, plastic, paper, metal, and others. For multi-objective optimization of network design, one of the interesting fields of research can be the combination of service level for recycling with cost and CO_2 emission.

Optimization of recycling network

Credibility based fuzzy mathematical programming models can be introduced to recycling design under uncertain conditions. Researchers could aim to minimize environmental impacts and the total cost of recycling network establishment for both dynamic nature and uncertainty with optimization and simulation. Concentrating on network design is another interesting point of research that can be explored with regards to transportation within the recycling network. To understand the impact of transportation on the environment, studies can be conducted for centralized collection system and processing of EOL products in different industries like automobile, paper, plastic, metal, iron, and other industries.

An extension of the network design for recovery of used products in a fuzzy environment is an interesting topic for research. This requires realistic assessments within diverse industries. Fuzzy logic designed for multiple product recovery within multiple return periods will be supportive in finding solutions for more complex network with disposal centre in favor for hazardous materials. Standardized disposal of hazardous elements in the landfill requires detailed study and analysis for better understanding of the environmental impacts. Simultaneous design of delivery routes and returns strategy development for numerous stoppages or customers is a challenging area. It can further extend to double uncertainty including randomness and fuzziness.

Take-back and collection of EOL products

Segregation and collection of reusable products with the inventory management in the reverse supply chain is a great challenge. To manage the continuous flow of reusable products, some improvement areas need to be identified in the collection centers. In this case a new strategy could be competition among the collecting parties of cores or reusable parts and products. Further analysis on the situation and simulation-based study for multiple suppliers or parties that collect cores or reusable products could be performed. A study on the quality of collected materials by incorporating quality uncertainty of collected materials into procurement planning is also highly necessary.

Inventory management of collected materials for recycling is another great area of research from the point of view of carbon impact of the inventory of recycling. Managing carbon footprint and price in inventory management of recycling where demand is stochastic is a challenge for researchers. Different simulated inventory models can be applied to calculate the carbon impact of the inventory of recycling.

Environmental footprint

An important point for research can be the integration of recycling with environmental footprint and its application to various industries. Extensions should be applied for multi-echelon calculation rather than consideration of a single stage only. Standardization of the different strategies of reverse logistics with a combination of environmental footprints will be beneficial from both manufacturers' and social perspectives.

V. Conclusions

The review shows that recycling is different from forward logistics. Basic stages of recycling have been identified, with some subdivisions. Review also shows a growing number in research publication on recycling especially after 2005, but in recent years the focus is the consideration of cost and environmental factors related to the different

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operations of recycling. Hence, recycling is considered as one of the major drivers of green supply chain and logistics.

In this review, content analysis was adopted to show a complete perspective of the recycling system. A major perspective that needs to be considered in a recycling situation includes not only network and inventory analysis, but also collection of used products and their use, resale, and remanufacturing through an established system. Moreover, this review connects the scopes of environmental footprint analysis within the major stages of recycling. The review also shows that in recent time research is also focusing on environmental factors in price sensitive ways in order to attract used products from the customers. Therefore, the challenge to the decision makers in reverse logistics business is not only to set up an economically efficient network but also an ecologically efficient system in such a way that used products are received at the expected time, price, and quantities. Subsequently, remanufacturing needs to be performed more efficiently, economically, and environmentally friendly compared to the production of new products.

Furthermore, the review shows that while the life cycle is cradle to grave in an open loop system, it is now replaced by cradle to cradle in a closed loop perspective to achieve better utilization of all types of waste. The cradle to grave perspective can be shifted to cradle to cradle perspective by integrating manufacturing and remanufacturing, designing and assessment of EOL product, and decisions for returned product.

Finally, the review proposed some important directions regarding recycling research. It is obvious that research can be strengthened in the assessment of the stochastic nature of supply and demand of remanufactured products in environmentally friendly manner. Future studies can develop more environmentally friendly and cost-effective ways of recycling to meet the challenges of the upcoming centuries and environment.

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