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Towards Sustainable Polymeric Materials: Zero Waste, Green and Self-Healing

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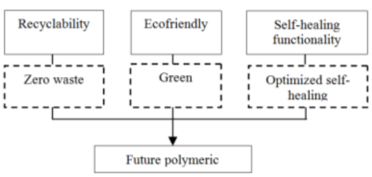
Graphical abstract



Abstract

Although polymeric materials are widely adopted in various applications, the sustainability of the materials is often controversial, particularly on the current handling of polymeric wastes and the use of non-renewable resources as raw materials. A brief review is hence given to outline recent efforts that promote sustainable value of the materials. The discussion starts with the recycling activities of polymeric wastes. Next, the concept of ecofriendly composites, which include bio-based and biodegradable, is discussed. Then, a note on inclusion of self-healing functionality in polymeric composite that is seen as another promising methodology in meriting the sustainability of polymeric materials is offered. Furthermore, the feasibility and possible improvement of the aforementioned methodologies (i.e. zero waste and green concept) are highlighted and discussed. In conclusion, more research works on the individual or combination of the improved methodologies and a concise evaluator are needed to extend further the sustainable potential of polymeric materials.

Keywords: Polymer; sustainability; waste hierarchy; zero waste; green; self-healing

1.0 INTRODUCTION

Materials in the world could be commonly categorized into four main groups, namely metals, ceramics, polymers and composites (i.e. any combinations of the former three). Polymer itself could be subdivided, by the nature of the material, into thermoplastic and thermoset. When additives are added to polymer (i.e. usually for the properties improvement), the resulting material is termed as plastics.

Today, the use of polymer and its composites is in a much steeper increasing trend than its other opponents. The main advantages of polymer include lightweight, versatile and durable, to mention but a few [1]. One finds its major applications in packaging, building and construction, automotive, electrical and electronics, agriculture and others where the first two categories constitute over a half of the total consumption [2].

Though perform satisfactory in both structural and non-structural intensive applications, the polymeric materials possess several weaknesses from the perspective of sustainability. One of the chief and well-known issues comes in the form of the waste management. The failure in ensuring a proper waste treatment of polymeric wastes endangers the ecosystem due to the possible leaching of the toxic components (i.e. usually additives) embedded within it [3]. Even if the collection is accomplished, its common ways of disposal, namely landfill and incineration, offer none or insignificant sustainable merits [2]. Moreover, it is generally agreed that these activities could induce pollution problems as a direct product. The much promoted sustainable management of waste, namely recycling and re-use, is generally not practical for large scale implementation due to its inherent complex nature.

Next, most of the commercialized polymeric materials are derived from the petrochemicals, i.e., non-renewable resources. The continuous depletion of resources, which may sacrifice the benefits of the next generation, collapses the core objective of sustainable development. Besides, the use of these precious raw materials to produce the often single-use products with relatively short service life (i.e. packaging industry which constitutes the largest portion of annual consumption) is generally judged to be non-sustainable.

The discussion on sustainable development has been arisen actively since the last decade due to the new framework of global legislations (i.e. focusing on sustainable development) and general public awareness. All parties, ranging from industry user to academician, have been trying to implement sustainable design whenever/whichever possible. It is stressed that the lack of discussion, focusing on sustainable methodologies, as a whole with specific reference to the polymer materials in the literature is highlighted as the open issue that offers the ground for the critical need for present discussion. While the existing discussion from literature is scattered due to various possible perspectives and mostly specific, it is the aim of the present article to gather and unify approaches correspond to sustainable aspect of polymeric materials in this brief review. Since each aspect has its extensive literature, only relevant and mostly the latest (i.e. since 2010) opinions are selected to be included in the present discussion. Though seems general, it is hoped that the unified discussion as highlighted in the present article could give the interested readers a quick but yet comprehensive grasp on the sustainable aspect of polymeric materials. Note that the current brief review by no means wholesome in the sense that it covers only polymeric materials, it is however offers a topic hitherto not been explored in the present angle.

In this article, the efforts in contributing the added sustainable values to polymeric materials are briefly reviewed. In Section 2, the recycling efforts as a sustainable alternative to the current handling methods of polymeric wastes are listed and discussed. In Section 3, the development and importance of bio-composites with degradable feature are examined and discussed. The inclusion of self-healing functionality into polymeric materials as a promising method to further extend the sustainability of the materials is reviewed in Section 4. In Section 5, the discussion is focused on the feasibility and potential improvement for the existing methodologies. Finally, the article ends with some suggestions for the development of sustainable polymeric materials.

■2.0 WASTE HIERARCHY OF POLYMERIC WASTES

The waste hierarchy is a general rule of thumb for the waste management options, which is ranked mainly based on the environmental perspectives. The main components of the hierarchy (i.e. from most preferable to least) include reduce, reuse, recycle, recovery (i.e. composting and incineration) and landfill.

To date, the most common disposal ways of polymeric wastes are incineration and landfill [2]. Other alternatives, though exist, are less practiced due to the lack of public engagement (i.e. reduce), feasibility of the option (i.e. reuse and composting), and cost-effectiveness consideration (i.e. recycling).

Though landfill of polymer wastes is one of the main streams for disposal, it has been criticized to hardly give any significant sustainable merits [4-5]. Moreover, new legislations and longevity of polymeric material that limits degradability, both constrain the available space for land filling in the near future, are generally reported to cause the formerly economic activity to be graded as a non-feasible option.

On the other hand, incineration for energy recovery (i.e. heat and electricity) is examined to be much sustainable compared to the landfill option and it somehow becomes a better alternative [4-5]. Nevertheless, the detrimental environment impact induced in performing such activity needs to be justified with the benefits of such energy recovery before a more conclusive opinion on the sustainability is made [6].

The 3R's concept (i.e. reduce, reuse and recovery) is often reported to be much sustainable in the waste hierarchy and served as preferable options compared to landfill and incineration. The recycling is currently the highlight of these options due to its relative ease in implementation, based on the waste generation scenario nowadays, and hence laid herein as the base of the further discussion.

Ignatyev *et al.* [7] categorized polymeric wastes into end-of-waste (EOW), end-of-live (EOL) and post-consumer (PC) where they are generated during production and at the end of service life, respectively. Primary mechanical recycling is mainly suited for EOW while secondary mechanical recycling is for other streams (i.e. EOL and PC) – both for the purpose of material recovery. Meanwhile, all polymer wastes could undergo chemical recycling (i.e. also known as tertiary recycling) and combustion for energy recovery. An overlook on the status and challenges for these recycling methods has been previously given [7]. Al-Salem *et al* [8] reviewed and discussed the aforementioned recycling methods for polymeric wastes where primary mechanical recycling (i.e. also known as re-extrusion) is reported to constitute major portion (i.e. > 95%) of the recycling of polymeric wastes. Hamad *et al.* [9] provided a review on both the mechanical and chemical recycling efforts on the popular petroleum-based polymer and their systems (i.e. blends and composites). They reported that mechanical recycling is much preferred than chemical recycling due to the cost-effectiveness. Also, blending techniques in the presence of compatible agents is found to improve the properties and hence the market value of the recyclates generated from the mechanical recycling.

Apart from the polymeric materials, the recycling of its composite wastes is reviewed herein. Asmatulu *et al.* [10] had identified several challenges in performing the task of the recycling of polymeric composites, which include low recyclability of the materials due to its inherent nature, contamination of the wastes, efficient recycling system (i.e. collection, classification and separation), uncertainty on the continuous supply of wastes and poor existing recycling techniques. Despite these difficulties, the recycling efforts using mechanical, chemical and thermal method are reviewed and compared. It is found that the chemical recycling outperforms the mechanical and thermal recycling in producing the recyclates (i.e. fiber) that possess a higher tensile strength. Oliveux *et al.* [11] performed a review on the recycling of fiber reinforced polymers and concluded that the recycling effort should be selected according to the nature of the wastes and its further intended application. Yang *et al.* [12] offered an extensive review on the recycling efforts based on type of polymer (i.e. thermoplastic and thermoset) where it is observed that most of the research activities are focused on the thermoset-type waste due to its lower recyclability. Besides, the recent composite recycling activities in aerospace, automotive and wind energy industry were reported and discussed.

■3.0 ECOFRIENDLY POLYMERIC MATERIALS: BIO-BASED AND BIODEGRADABLE

One of the main alternatives in providing an added sustainable value to the polymeric materials is through the use of biomass as raw materials for the production. Apart from conserving the non-renewable resources (i.e. petrochemicals), the bio-based polymer possesses better recyclability, and hence contributing to a greater environmental advantage to these materials. Besides, the replacement of synthetic fibers (i.e. glass and carbon) with the natural fibers to form bio-composites is another sustainable potential for polymeric composites, which is also based on the route of adoption of renewable resources.

Soroudi and Jakubowicz [13] and Faruk *et al.* [14] reported the manufacturing and applications of bio-based polymers and their blends and composites (i.e. also known as bio-composites). Also, the recycling activities related to the bio-composites are discussed [13]. Zini and Scandola [15] discussed the major environmental benefits arising from the development of bio-composites and listed the commercialized products based on the thermoset and thermoplastic matrices.

The durability of the polymeric materials (i.e. non-degradable), though advantageous for the use-phase, is limiting the waste management options of its wastes. The inclusion of degradability in polymeric materials is seen as new alternative to enhance the sustainability of the materials.

Song *et al.* [16] reviewed the bio-composites that possess the capability of undergoing biodegradation and compost. Apart from providing extra waste management options (i.e. rather than landfill, incineration or recycling), it is generally agreed that these methodologies do not exert any pollution issue if the activity is performed under a controlled condition. Niaounakis *et al.* [16] gave a comprehensive review on both the biopolymer and their blends that are commercially available and their general applications. Yazdi *et al.* [18] discussed bio-composites in terms of the development, potential issues and applications of the materials.

■4.0 SELF-HEALING POLYMERIC MATERIALS

van der Zwaag *et al.* [19] reviewed the methodologies to include self-healing functionality in polymeric composites. Generally, there are extrinsic and intrinsic types self-healing system, which are designed to suit the thermoset and thermoplastic nature of the polymeric material, respectively. The chemistry of cross linking of these systems was discussed by Billet *et al.* [20] and Wu *et al.* [21]. The potential in extending the service life, hence reducing production for new replacement and later the generation of waste, is the main sustainable advantages of these materials.

Zhang and Rong [22] discussed the works on the theoretical modeling of the self-healing mechanisms in polymers. Besides, few initial works attempted on the design of optimized healing system for polymeric materials are reviewed.

Aïssa *et al.* [23] categorized the self-healing materials according to the nature of the polymeric matrix (i.e. thermoplastic and thermosets) where more works devoted to thermoset-type composites was reported.

Murphy and Wudl [24] discussed the healing system of the polymeric materials based on the stimulus used to trigger the repairing mechanisms. Generally, there are autonomous (i.e. mechanical) and non-autonomous triggers (i.e. thermal, electrical, electromagnetic, ballistic and photo) which are categorized on the level of human intervention. Mauldin and Kessler [25] reviewed the healing system of polymeric materials based on the mechanisms adopted, namely crack filling, diffusion and bond reformation. Also, the practicality of the self-healing concept, based on the gathered literatures, was discussed where the economic feasibility and reliability of the healing system were identified as the key obstacles to the large-scale implementation.

Blaiszik *et al.* [26] discussed the assessment methods adopted for the evaluation of the healing efficiency of both intrinsic and extrinsic healing system.

Zhu *et al.* [27] gathered the recent efforts in promoting the regain of non-structural properties of damaged polymeric materials, some of which are the major reason for the obsolescence of these materials due to the loss of the inherent properties (i.e. electrical/thermal conductivity and corrosion resistance). The repair of these properties not only extends the service life time but also reduces significantly the wastes generated from the targeted applications that constitute almost half of the annual consumption (i.e. packaging and electronics). Moreover, the regain of the properties could be regarded as the shifting of the single-use component to multiple-use-like components and hence balances (i.e. at least partially if not completely) the use of precious resources for the production of these user products. These two main benefits contribute to the sustainability merits of the self-healing functionality of polymeric materials. Moreover, these materials have been reported to be compatible with the aforementioned sustainable methodologies, namely recycling [28] and ecofriendly composites [29-32]. The combination of these methodologies (refer Figure 1) seems promising in further enhancing the sustainable value of polymeric materials.

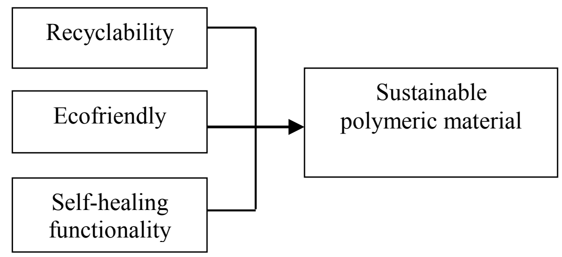


Figure 1 Current methodologies towards sustainable polymeric materials

■5.0 AN OVERVIEW OF THE SUSTAINABILITY: RECENT AND FUTURE

The current focus of waste hierarchy is to reduce the landfill and incineration activities of polymeric wastes by the substantial increment of the recycling activities. Though providing sustainable merit by generating raw materials (i.e. recyclates) for the new products from polymeric wastes, the activity has been reported to give several environmental and health risking impacts [33].

New focus has been shifted to higher rank of the waste hierarchy, namely reduce and reuse. The overall efforts could be summarized in the 'zero-waste' concepts [34], which evolve from the waste handling to waste eliminating, and hence providing the greatest sustainable value.

Next, the use of biomass in producing bio-based polymeric materials has found to induce the potential to compete with the food industry. Niaounakis *et al.* [17] reviewed the current feedstock for the production of biopolymers where there is a shifting trend to the use of no-edible biomass and alternative sources as an alternative to the concerns.

While the bio-based and biodegradable polymer is progressively developed, the inclusion of clean production [35], which ultimately leads to the implementation of green concept within the whole life-cycle of the material (i.e. extraction of raw materials, manufacturing, use and disposal), is believed to be the next future of sustainable polymeric materials.

Generally, the development of self-healing polymeric materials is still at its infancy stage. The inclusion of such functionality is doubted, if possibly induce any consequences (i.e. from manufacturing to use to disposal), to compromise the existing sustainability of polymeric materials**.** Also, most of the demonstrated specimens nowadays are to date still far from the optimized stage, mainly due to the lack of standardized framework [36, 37], and hence is worthy to be focused in future works.

Based on the discussion in this section, it is noticed that further constructive improvements from the existing practicing methodologies in resolving the sustainability issues of the polymeric materials are needed. The next level improvement of the major methodologies as discussed in previous sections, either solely or in combination, as demonstrated in Figure 2 is generally believed to be the key to success.

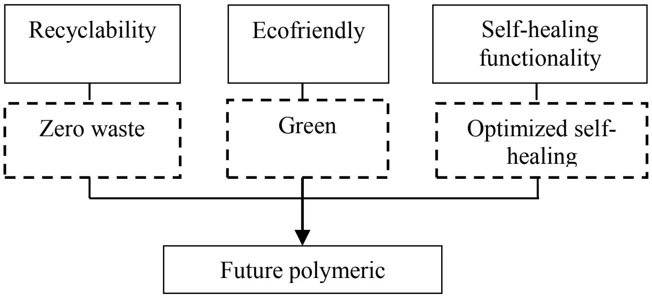


Figure 2 The future of sustainable polymeric materials

■6.0 CONCLUSION

A brief discussion on the major existing methodologies in pursuing sustainable value of polymeric materials is given where most of the latest opinions have been included. The promoting of the recycling activities is noted, as a much sustainable approach, aiming to reduce the management of polymeric wastes using landfill and incineration activities. The use of renewable resources as raw materials for the production of polymer based product is another urging sustainable approach. Also, the inclusion of healing ability within the damaged polymeric materials is another updated approach in enhancing the sustainability of the materials.

Though seems promising as an ultimate sustainable methodology for polymeric materials, the development of bio-composites that possess both the recyclability/degradability/compost ability and self-healing functionality is rare in the literature. The use of life cycle assessment, one of the most promising tools, in evaluating the sustainable potential of each route remains doubtful. Sufficient data input and concise assignment of system boundary, which is mainly based on the research efforts and practices, is generally believed to play a vital role in justifying the best future path towards sustainable polymeric materials. In closing, it is recommended that more research and a concise evaluator are needed to measure the degree of sustainability of polymeric materials.

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