IOP Conference Series: Materials Science and Engineering

Degradation and stability of polymer: A mini review

To cite this article: N Sazali *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **788** 012048

Degradation and stability of polymer: A mini review

N Sazali[1, 2,*], H Ibrahim[1], A S Jamaludin[1], M A Mohamed[3], W N W Salleh[4] and M N Z Abidin[4]

[1] Faculty of Mechanical and Manufacturing Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia.
[2] Centre of Excellence for Advanced Research in Fluid Flow (CARIFF), Universiti Malaysia Pahang, Lebuhraya Tun Razak, 26300 Gambang, Kuantan, Pahang, Malaysia.
[3] Centre for Advanced Materials and Renewable Resources (CAMARR), Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia.
[4] Advanced Membrane Technology Research Centre (AMTEC), School of Chemical and Energy, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor Darul Takzim, Malaysia.

*Corresponding author: azlianie@ump.edu.my

Abstract. Observations of alterations in the structural and chemical properties have been commonly performed to understand the process by which polymers degrade. The validity of each observational procedure depends primarily on the test material and type of degradation. An appropriate method for the characterization of polymers can often be utilized to examine the properties of degradation. The service life of a polymer depends strongly on the conditions to which the material is subjected. On the other hand, the stability of the material, including nanocomposite polymer blends, often dictates its usefulness. Thus, this review was aimed to evaluate the degradation of nanocomposite polymer blends, with specific focus on the role of the fillers and the composition of the blends. The factors that could significantly affect the degradation of the same were the presence of a filler, as well as the morphology and composition of the blends.

Keywords. Polymer blends; Compatibilization; Photodegradation; Thermal degradation; Stability

1. Introduction

Being a relatively new and rapidly-expanding field, membrane innovations offer numerous benefits (e.g. energy productivity, cost-effectiveness, and environmental friendliness) over the conventional partitioned procedures. In addition, layer innovations can easily be combined with other partitioning strategies to improve the efficiency of the overall process as well as cut down the cost of detachment. Figure 1 shows the schematic graphs of two types polymeric membranes for separating gas which can considered as cheap and energy-efficient tools. However, its relatively lower thermal resistance restricts its utilization in certain industries. While some polymeric membranes can be run in extreme conditions, the need to cool down hot streams for example, will cancel off the energy- and cost-efficiencies of the technology, thereby rendering it impractical [1-3]. In view of that, polymer modification efforts have been made to come up with synthetic polymeric membranes which can withstand high temperatures.

Thermally-stable polymers – especially carbocyclic and heterocyclic ones – have been introduced by scientists [2]. Yet, these polymers are poorly soluble in common organic solvents and have high phase-transition temperatures. Despite their low processability, some studies have reported the successful utilization of thermally-stable polymers to produce membranes with satisfactory separation characteristics and performances [2, 4, 5]. The future trajectory of the gas separation field entails full exploitation of the advantages of thermally-stable polymeric membranes for market-worthy performances. The said polymers can be made up of a single repeat monomer (homopolymers) or two or more monomers (copolymers), apart from being either amorphous or crystalline [6]. Generally, most polymers have both amorphous and crystalline regions, the latter of which gives rise to a stronger polymer since the tendency of slippage between the chains is lower [7-9].

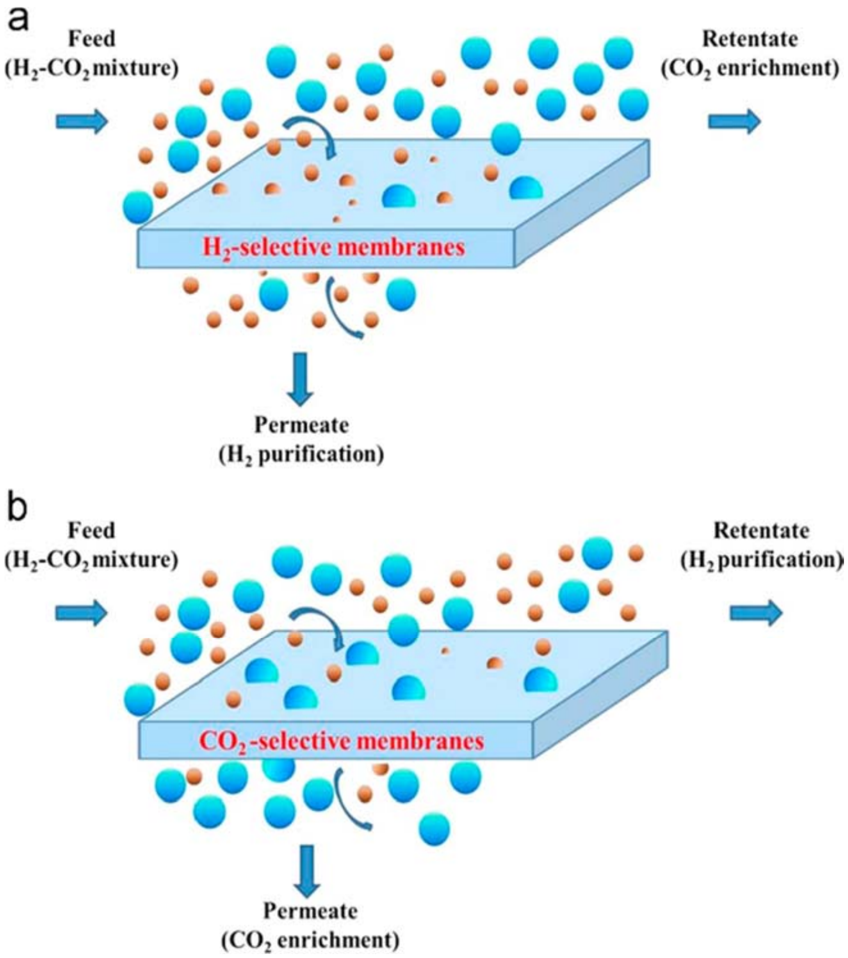

Figure 1. Schematic diagrams of (a) H_2-selective membranes and (b) CO_2-selective membranes [10].

Below glass-transition temperatures [Tg], polymers form a hard structure, and vice versa. Subsequent to their discovery, synthetic polymers have been employed in various applications. Tailoring of the polymers' properties will produce polymeric devices of different strengths for use in biomedical (e.g. pharmaceutical, medical, dental, food, and cosmetic) industries [11-13]. The way by which a polymer degrades following its implantation in a biological system can determine whether it is biodegradable or non-biodegradable. Usually, polymers with C-C backbones are highly resistant to degradation while those with heteroatoms (i.e. esters and anhydrides) are susceptible to degradation. Figure 2 summarizes the stages involved in the degradation of biodegradable polymers, where the primary mode of degradation is chain-cleavage via hydrolysis (either through abiotic/ non-enzymatic hydrolysis or enzyme-promoted hydrolysis). On the other hand, polymers which are very resistant to hydrolysis are characterized as oxo-degradable systems [14].

2. Overview of polymers degradability and durability

Natural degradation refers to the changes in the properties of a material following exposure to natural outdoor conditions, namely sunlight (directly or indirectly), heat, oxygen, moisture, and other factors. The types of polymer degradation are shown in figure 3. Microorganisms, ozone, airborne chemical pollutants (e.g. sulfur oxides and nitrogen oxides), and salt are some of the external factors that can exert a significant impact on the process of degradation. Furthermore, these environmental agents will also act on other components – such as dyes, pigments, processing additives, absorbers, and stabilizers – that reside within the polymer matrices.

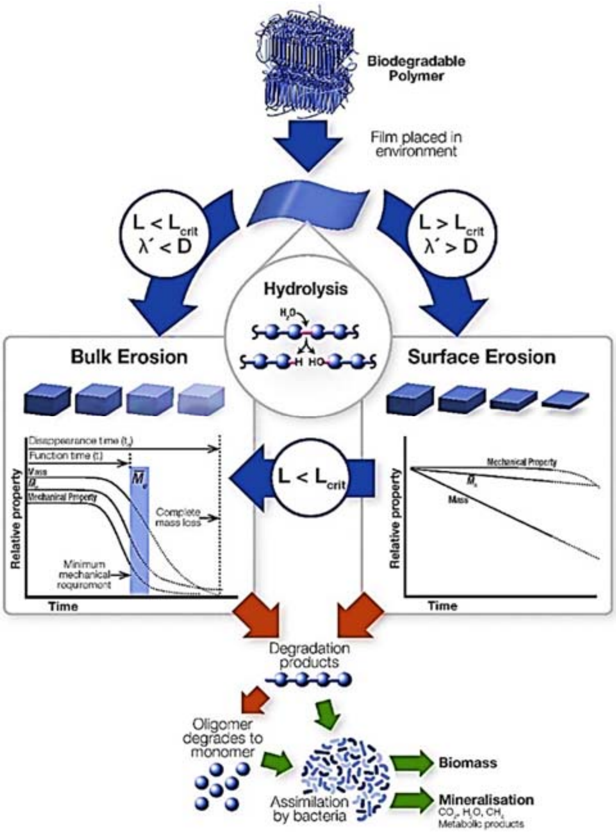

Figure 2. Steps involved in polymer biodegradation by hydrolysis [14].

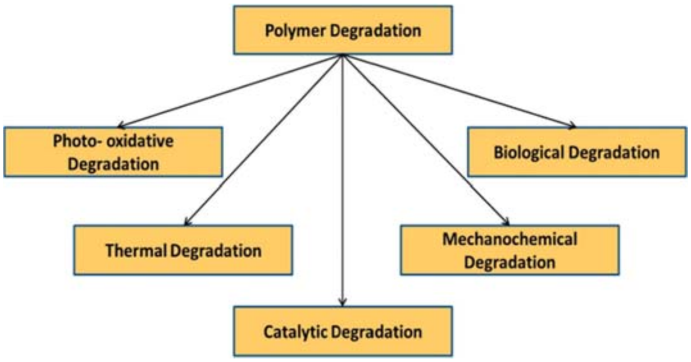

Figure 3. Types of polymer degradation.

Each aforementioned component is subject to environmental effects individually or in combination. Accordingly, various factors in a typical habitat – sun-based radiation, temperature, moisture, oxidative conditions, and mechanical toxins – can act intelligently via a debasement procedure. Therefore, the general impact of degradation can be greatly complex. With reference to the basis above, polymer degradation is categorized into thermal debasement (heat), thermo-oxidative debasement (heat and oxygen), thermomechanical debasement (heat and stress), photo degradation (light), photo-oxidative corruption (light and oxygen), biodegradation (natural operators), mechanical debasement (mechanical stress), and so on. A polymeric material will typically experience warm, thermo-oxidative, and photograph oxidative debasements throughout its preparation and utilization. Figure 4 shows the types of degradation and stabilization pathways of polymer.

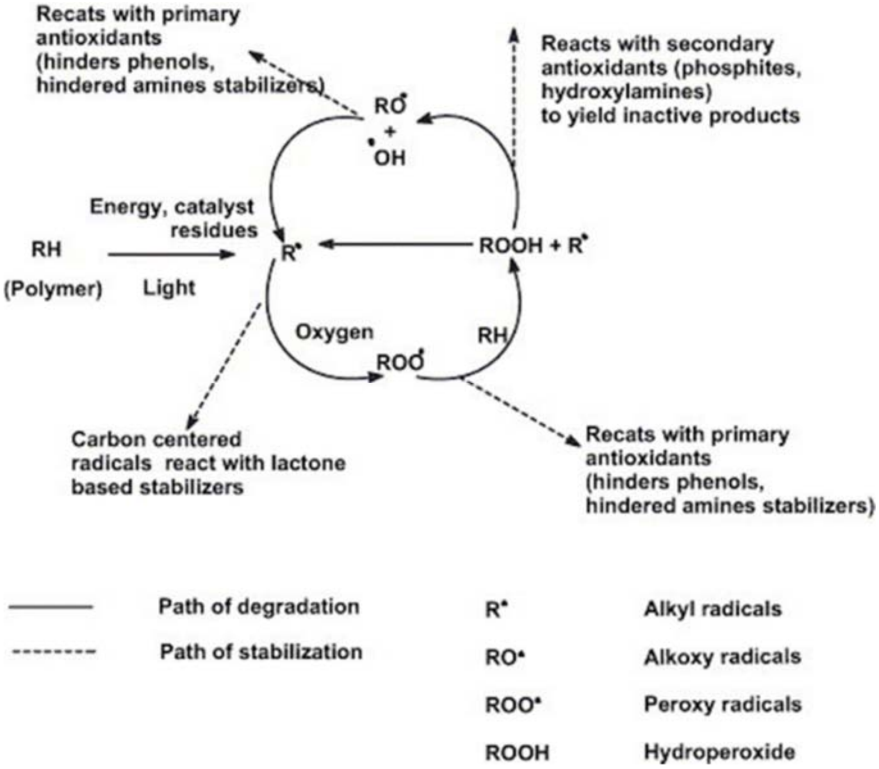

Figure 4. Different pathways of degradation and stabilization [15].

It is commonly accepted that the degradation is an irreversible process. Chemical degradation of polymers for instance, significantly affects their performance including the daily-used plastic materials. Commonly, the change of polymer properties from its initial state, either desirable or not is called "degradation" [16]. Thus, degradation can be considered as a generic term for all kinds of reaction in a polymer [17, 18], usually involving a number of physical and/or chemical processes with small morphological changes. These processes can lead to significant decline of the polymeric material quality i.e. poor mechanical or electrical properties, before finally losing its functionality [13, 19]. In biological tissues, polymers undergo degradation by means of hydrolytic or enzymatic lysis of their polymeric bonds, thereby forming waste metabolites. Evidently, hydrolytic degradation of polymers is preferred over its enzymatic counterpart since the polymers undergo a more consistent degradation rate at different sites of the body [13, 17, 20]. As a side note, biodegradable polymers include natural polymers (i.e. cellulose), modified natural polymers (i.e. cellulose acetate), or chemically-synthesized polymers. Synthetic biodegradable polymers are largely favored since they can be modified to improve the consistency of their degradation behaviors and properties [20]. Chemical degradation significantly affects the performance of the polymers, including plastic materials of daily used. Throughout degradation, polymer oxidation (mechano-oxidation) produces hydroperoxide, which affects the thermo-/photo-oxidation rate during the subsequent aging and weathering. Information of the mechanism of polymer degradation has facilitated the development of efficient stabilizers and sensitizers to enhance the performance of the product [19, 21], and produce environmental-friendly (biodegradable) plastics respectively [22]. Biodegradation can be achieved by any one of the ways as shown in figure 5 [23]. Evidently, polymer degradation has both harmful and beneficial aspects. In terms of the former, reduction in polymeric performance and manifestation of safety hazards can occur if the process is left unchecked. Otherwise, with proper management, it can be utilized to create new and promising materials [13, 24, 25].

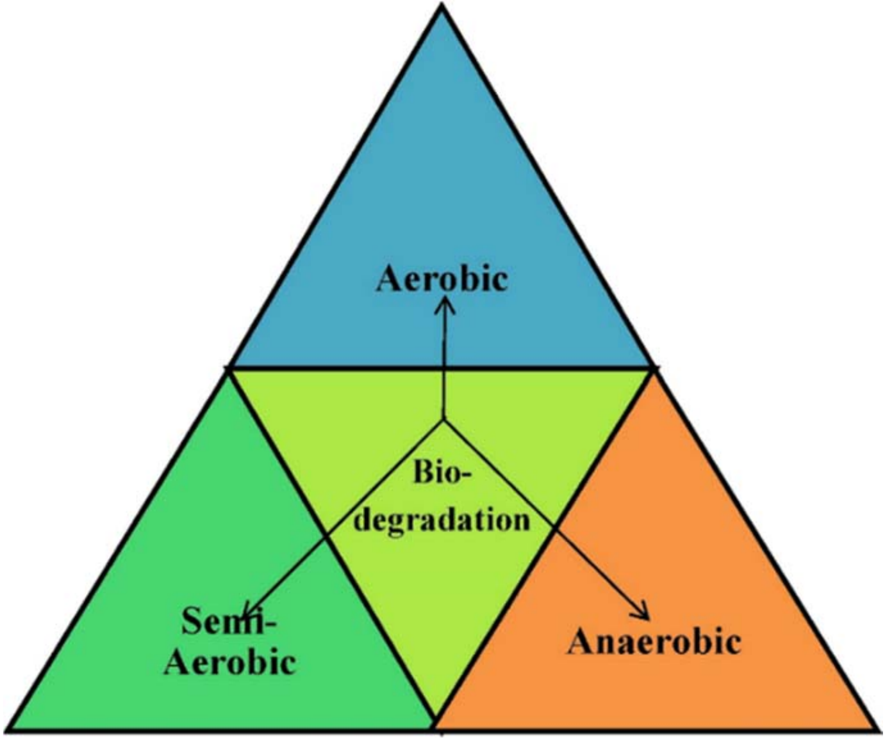

Figure 5. Biodegradation pathway to treat plastics [23].

Artificial weathering gadgets are instruments for acquiring data with respect to the potential debasement behaviors of polymeric materials. In spite of the fact that these gadgets have certain inadequacies, they still provide valuable data on the behaviors of the said materials. The most-preferred feature of research gadgets is that they accelerate the debasement of the test materials. This can be achieved either by extending the time of exposure to the environmental factors (e.g. persistent exposure to artificial light, heat, and wet/dry cycles) or increasing the intensity of the variables. Specific stabilizers can be incorporated into a polymer framework to protect the latter from the ecological variables. Hence, information of the debasement of the polymer is highly essential for enhancing the strength and security of the material. By and large, debasements can be evaluated by observing the progressive changes in the structures and properties of the polymers. One benefit of a touchy procedure is that it enables the time of initiation of debasement to be identified, thereby reducing the amount of time required for assessments. Despite the legitimacy of the aforementioned method, the relationships between the outcomes to the commonsense material execution (e.g. carbonyl compound development versus embrittlement) need to be determined.

In most cases, the introduction of additives may alter the service lives of polymers. For instance, sensitizers can be introduced to promote the oxidation of polymers via the production of singlet oxygen (1 O2) molecules which results in energy transfer to the polymer or its self-decomposition [26, 27]. In addition, stabilizers can be added to the polymers to improve the latter's durability by minimizing the rate of degradation or by protecting them from environmental factors [28]. The disadvantages of the utilization of the single-additive system include compatibility issues, migration of low-molecular weight stabilizers, immobility of high-molecular weight stabilizers, and inadequately efficient organophosphites. Excellent protection against degradation can arise from the synergistic effects of screeners, quenchers, ultraviolet absorbers, and antioxidants [29]. To overcome the evaporation and migration problems, higher molecular weight stabilizers – which are usually polymers – can be added. These stabilizers can be produced via three methods:

- Stabilizer-polymer grafting;
- Homo-/ co-polymerization of monomers anchored with stabilizers;
- Incorporation of photo-rearranging polymers as additives.

Sensitizers or stabilizers are commonly employed to enhance the properties of polymeric materials, especially during the preparation of nanocomposites [9]. Generally, an equilibrium between execution and operation times is required for all materials, including polymers [30]. Unlike polymers which originate from renewable resources, petroleum-based ones are cheaper to produce and frequently perform better in any application. Thus, the idea is to utilize polymers with long lives to enhance the performance of their short-lived counterparts (such as biological polymers). Ultimately, to achieve this goal, the study approach should entail the management of the production-service-waste process with respect to the three pillars of sustainability, namely Planet (environmental pillar), People (social pillar), and Profit (economic pillar). In particular, the sustainability of bio-based polymers is a theme which has been put forward because of its significance with regards to the environment, technological development, and economic growth [31, 32]. In view of the decent potencies and capabilities of the most commonly-used petroleum-based polymers, bio-based ones need to be meticulously modified in terms of properties like modulations, applications, and disposal methods so that the valorization, service conditions, and/ or discarding of the said polymers fulfil the expectations. Moreover, the aforementioned processes have to be financially and economically efficient, and environmentally friendly.

The selection of suitable materials and synthesis methods is paramount in order to ensure that the applications of bio-based polymers perform well with respect to their long-term properties [33]. There needs to be a balance between the performance and processing of these polymers. Thus, the end-of-life fates of bio-based products should not only be determined with respect to the carbon life cycle, but also from the perspectives of their valorization in feedstock, conversion into distinctive materials, as well as vitality [34, 35]. In this case, the long-term properties of polymers are reflected by the durability of the materials in the presence of degrading factors such as humidity, temperature, or sunlight. The next three sections concern the energetic, biological, and material valorizations, all of which are essential to enhance the values of the polymers with respect to their expected end-of-life and performance prospects. To sum up, the current research has proposed various methods to improve the end-of-life and long-term properties. The specific purpose of this exercise was to expand the literature on the maintainable and sustainable designs of bio-based polymers [36].

2.1. Degradation and durability properties and end-of-life of polymers

The terms "durability" and "degradation", as well as "long-term properties" and "end-of-life" of polymers, are related to one another. Degradation refers to a process which results in the deterioration of any physical property of a polymer. In general, the said process starts at the amorphous/crystalline interface, and affects the mechanical properties, thermal stability, distribution of lamellar thickness, as well as crystallinity. The distinct aspects of each term will be demonstrated with respect to the scope of the analysis in question. Although bio-based polymers are expected to perform well, the improvement of their long-term properties is determined by the extent to which their strengths are conserved. It is essential to monitor and select the most effective degradation pathways to eliminate plastic waste [37]. Evidently, these two aspects should be taken into consideration during the selection of appropriate materials for particular applications. In addition, a balance between the simple end-of-life pathway and durability of a plastic product needs to be struck in order to minimize the negative impact on the environment. Instead of the end-of-life of a material, the end-of-life of a polymer should be considered instead so as to provide such products with second-life uses. This in turn will enhance the service-life and value of the polymer. A simple method to realize the above idea is by sending discarded polymers to downgraded applications, for which they will be incorporated into other materials to improve their applicability, generate energy or feedstock, or recoup carbon sources [38, 39].

The physicochemical properties of bio-based polymers are subjected to different operations or evaluations of the applied valorization conditions. Specifically, the maintenance of the performances of the polymers, or the monitoring of the extent of degradation, will guarantee the appropriate valorization of the materials. In this case, the evaluations of the properties began with a miniaturized approach (i.e., structure-morphology), culminating in macro-response assessments (i.e. thermal or rheological properties, mechanical characteristics, interfacing with the application at the durability stage and with the environment, effects on the environmental and human well-being, release of low-molecular weight compounds during degradation, durability, as well as reenactment of service conditions).

2.2. Thermal degradation

Thermal degradation refers to the heat-induced deterioration of chemical compounds into smaller components which do not recombine after cooling. In the case of polymers, this process is divided into four categories:

- Degradation occurring below glass transition temperature, which can initiate basic alterations known as physical aging;
- Degradation occurring between glass transition and melting temperatures, which results in the loss of dimensions owing to the transformation of the material into a more crystalline structure or the decomposition of the low molecular weight additives;
- Degradation occurring between melting and decomposition temperatures, which an extremely important piece of information in ensuring the processability of second-life bio-based goods; and
- Degradation above decomposition temperature, which is also referred to as energetic valorization.

There are numerous methods for the evaluation of thermal degradation of polymers. The simplest one entails the use of ovens to detect the presence of impurities (e.g. moisture) without resulting in the decomposition of the main polymers [7, 40-42]. From there, thermal degradation is assessed in terms of molar masses and physicochemical properties. To evaluate thermal degradation (at temperatures up to the melting point or glass transition temperature), crystallinity, crystallization, as well as cold-crystallization temperatures or the crystallinity degree, Differential Scanning Calorimetry (DSC) is a feasible method. However, DSC is not suitable for the induction of thermal degradation at sub-glass transition temperatures since it consumes a lot of time. Rather, Dynamic Mechanical Thermal Analysis (DMTA) is a more appropriate method to test the impact of temperature on polymers [42]. Specifically, it can be used to evaluate the mechanical properties of polymers far below the melting temperatures by means of creep experiments. Finally, Thermogravimetric Analysis (TGA) is a very useful method to test the thermal decomposition of polymer-based materials in either inactive or oxidative conditions [43-45].

The growing interest and utilization of polymeric materials over the last couple of decades contributed to their commercial success, apart from giving rise to creative researches on the same. Even though this scenario is encouraging for the polymer-related organizations, the immense rate of utilization of these materials worldwide poses dangers to the nature in view of the accumulation of difficult-to-dispose waste materials [46]. As indicated by a study by Achilias et al. [47], 78 wt% of all plastic wastes are accounted for by polymers like Polyethylene (PE), Polypropylene (PP), Polystyrene (PS), Polyvinyl chloride (PVC), as well as those which contain epoxy resins and polyurethanes. Thermal degradation is not preferred in manufacturing and application. However, polymers with high thermal sensitivity can be degraded faster. This property is highly valuable for polymer squander administration and furthermore to recoup vitality. In view of the current challenges in landfilling and reusing polymer wastes, pyrolysis is a promising technique to overcome the issues [46]. In this study, polymeric materials were heated in the presence of oxygen under controlled conditions, thereby resulting in the breaking of the macromolecular structure. From here, oligomeric items and even monomers of interest can be created. For instance, the monomers, dimers, and trimers of styrene can be recouped into essential items via the warm corruption of PS. The degradation pathway of polymers can be controlled by modifying the reactant decomposition processes to yield profitable substances [48]. With the existing researches on waste-to-energy innovations, it has been discovered that catalytic fast pyrolysis (CFP) was an appropriate method to specifically convert biomass into high-quality biofuel. The processing of waste plastics via CFP can enhance the aromatic yield and reduce the coke arrangement [49].

Numerous reports on the thermal degradation of different polymers (i.e. polymers which have been used commercially and the progressing ones with their diverse blends and composite configurations) have surfaced in the past few years. The type of degradation is heavily dependent on the type of polymer and many other factors. Distinctive modern analytical instruments have been utilized to decide the key factors that trigger and sustain degradation following prolonged contact to heat in a latent environment [50]. Experiments have also been conducted in air to comprehend the role of oxygen in degradation. These analyses are especially helpful in the predictions of the administration lives and highest temperatures for the safe utilization of the material. Information on the same will be important in the determination of the capacities and applications of the end products, thereby promoting a more effective utilization of the existing materials. Awareness of the unpredictability of the outcomes of decomposition and the persistence of the chemical nature of the materials post-degradation can facilitate the development of appropriate safety protocols to minimize the associated hazards.

In light of these blending investigations, the corruption pathway systems and the response energies were created [51]. Nevertheless, exact predictions of the polymeric material reactions in thermal environments are still difficult to achieve. This is because the test results remain uncertain, and that the exact mechanisms of the procedure are, as yet, obscure. Hence, a more inclusive methodology needs to be devised to describe the degradation energies of polymers. Thermal degradation of polymer composites is a much more complicated issue because the fillers frequently influence the rearrangement of the polymers [52]. With the exception of the relatively new field of nanocomposites, there is surprisingly little information on the commercial viability of the composite frameworks; the overall strengths of unfilled polymers have not been taken into consideration. With reference to waste-to-vitality innovations, additional research is needed to come up with pyrolytic fluids with higher octane values which reduce the build-up of substances. This is turn gives rise to superb materials for the delivery of gas without much need for refining. An increase in the amount of rubber in dumps and landfills (the majority of which is accounted for by old tires) constitutes a nidus for ecological and fire hazards.

Pyrolysis of waste rubber is regarded as one of the most encouraging methods for the recoupment of significant items. The present routine with regards to the landfilling of waste polymers does not permit the recovery of the materials' esteem, apart from having natural outcomes, while modern mechanical reusing misfortune [53-55]. Hence, a more sustainable method is needed to better understand the recyclability and end-of-life issues of polymers, which would likewise build up a round materials economy [56]. Yao and Wilkie [57] have examined the heat degradation of PS, poly(sodium 4-styrenesulfonate), PSSNa, and poly(styrene-co-sodium 4-styrenesulfonate) copolymer blends of. Accordingly, they have demonstrated that the warm degradation of the blends occurs in two autonomous steps: when low amounts of PSSNa are present, there is direct inhibition hindrance of the corruption of PS. Conversely, when larger amounts of the former are utilized, there is an expanded arrangement of char which provides thermal protection. All in all, the phenomenon likely to occur when the temperature of corruption of the synthesized polymer is close to the moderately-high temperature of degradation of PSSNa. Naffakh et al [58] who examined the thermal decompositions of blends of poly(aryl ether ketone), PEEK, and a thermotropic fluid crystalline polymer (LCP), have found that the mechanisms of degradation were essentially expedited by mixing. In further detail, they have demonstrated that the mechanisms of corruption of the pure polymers were the same as those of the components of the blend. Hence, the abovementioned thermal degradation behavior was, for the most part, related to a higher corruption rate rather than an altered system.

2.3. Hydrolytic and hydrothermal degradation

In the case of bio-polymer, the most established type of bio-based polymer degradation is the hydrolysis of ester linkages. Therefore, polyesters account for the majority of such polymers in biomedical applications. There are two main ways by which biopolymers are hydrolyzed, namely passive and active methods which employ chemical hydrolysis and enzymatic reactions respectively. Evidently, the latter is more useful in natural polymers like Polyhydroxyalkanoates (PHAs) and polysaccharides. Polylactic acid or polylactide (PLA) and Polyglycolide (PGA) degrade via simple hydrolysis of their ester bonds – a process which does not require the catalysis by enzymes [48, 59]. During hydrolysis, a series of overlapping stages progressively reduces the molar mass and thus, alters the macroscopic physicochemical properties. The ISO10993-13:2010 protocol is usually employed to simulate the service-life conditions of biomedical materials. In short, this method involves the exposure of materials to an analytic medium (e.g. water, human fluid simulants, or phosphate buffer solution) for different durations at 37°C to mimic in vivo conditions. Degradation can be monitored in both liquid and solid fractions. On the other hand, for non-biomedical purposes, the ISO62:2008 (a modified water absorption protocol) can be used to accelerate the hydrothermal degradation of polymers. In this case, both water and temperature resembled the actual service conditions.

2.4. Degradable polymers

Of late, polymers have garnered a lot of attention owing to certain reasons. One simple example is the development of inflatable rubber tires. This would have been unlikely to happen without the use of natural or later, synthetic rubber as an energy-absorbing component. Moreover, materials like plastics have replaced some traditional materials as packaging in view of their superior physical properties (toughness and strength), lightness and barrier properties. Additionally, plastics have the ability to protect consumables against degeneration at low cost, thereby leading to improved distribution of foodstuff to the extent that plastics are now indispensable in modern retailing [60, 61]. Plastics are also more energy-efficient as compared with traditional materials [47, 62]. Relative to paper, the efficacy of plastics like polyethylene in protecting goods is around 1 to 2 by weight, which greatly reduces the consumption of paper and hence, deforestation rate [47]. However, the volumes of waste plastics, synthetic fibers, and rubber pose an increasingly serious problem to the disposal authorities. It used to be relatively inexpensive to dispose of domestic and industrial wastes in holes in the ground at the peripheries of towns and cities. Unfortunately, reductions in the number of such sites, coupled with the increasing bulk of the wastes, have led to an unacceptable increase in the cost of transporting packaging wastes to landfill sites.

There is also increasing awareness that societies should treat wastes as a resource by recycling the same into useful products rather than by burying them. Accordingly, in developed countries, it has become a responsibility for the producers of packaging to recover and recycle such materials that would otherwise have ended up in landfills [63]. It is now accepted, for reasons that will become apparent in the following discussion, that the term “recycling” needs to be broadened to not only include reprocessing or mechanical recycling, but also other methods for the conservation of the materials’ intrinsic values (e.g. energy- and biological-recycling). It is likely that hitherto the end of the second decade of this century, domestic and industrial wastes will be reused by means of a combination of these methods, and that only wastes with little or no potential value will be disposed of at sanitary landfills [47, 63, 64].

3. Photodegradation and stabilization

The functions of materials depend on their durability in the operating environment and the extent to which they interact with the environmental elements [65]. Therefore, information of the degradation and stabilization of polymer-nanocomposites are very crucial from the scientific and industrial perspectives. However, there are limited studies on these aspects. Only with an understanding of the mechanisms of degradation of the materials can the products’ service lives be prolonged. Nowadays, polymer-clay hybrids, which are being used in outdoor applications, are exposed to UV rays and other undesirable environmental aspects.

3.1. Photooxidation

With reference to outdoor applications, it is especially imperative to take into account the resistances of the materials to photo-oxidation. Evidently, even when polymers are subjected to ordinary utilization conditions, photo-oxidative degradation will still occur, which in turn leads to the general deterioration of their macroscopic properties because of the variety in molecular weights, compound structures, and morphologies [66]. The concentrations of the blends have an influence on the photodegradative behavior of a polymer mix. Evidently, these behaviors may not resemble those of the pure parts, connections among the distinctive species in the blends amid degradation and among the degradation items can happen. These chemical responses can either speed up the rate of degradation of the pure components or stabilize the impact [60]. The additional substances are not regularly connected in the event of the photostability of polymer blends and. As such, it is hard to estimate the photostability of the polymer blends with reference to the photoresistances of the unmodified parts. The photostability of PVC has been enhanced by its mixing with excess poly(vinyl alcohol) (PVA) [67]. Also, it has been demonstrated that the photostability of PVC/PVA blends was greater than that of unmodified PVC, even though both materials were less photostable than PVA. Specifically, in PVC/PVA blends, the number of carbonyl compounds was lower than the estimation derived from the additivity rule. Hence, this suggested that photooxidation prevented the formation of C=O to some degree in the blends. As a matter of fact, the photodecomposition of PVC/PVA blends relies on their connections between the segments.

The abovementioned negative impact was attributable to the way by which Cl radicals formed during the photodehydrochlorination of PVC react with the tertiary H molecules in the polystyrene of the MBS (one of the modifying agents used to improve the plastic properties) copolymer. The molecules then enter the Poly (methyl methacrylate) (PMMA) chains of the MBS copolymer to initiate the depolymerization of MBS. It has been reported that MBS hastened the photo-oxidation of PVC [68]. Apparently, peroxides break down into carbonyl and hydroxyl groups since the polybutadiene of MBS effortlessly forms peroxides in the presence of O_2. The accumulation of carbonyl groups in MBS can lead to the photoinitiation of PVC, thereby speeding up photo-oxidation. It is extremely cumbersome to predict the degradation behavior of a polymer blend with respect to the properties of its pure components is. The concentrations of the blends, in addition to the presence of a compatibilizer, can influence the degradation behavior of a polymer mix. As such, the behavior can have variable courses of corruption of the unadulterated segments since communications between the distinctive species in the blends and degrading substances take place during corruption. In this way, regular connections between the added substances are unlikely to occur during the degradation of polymer blends. This is in view of the fact that the rate of corruption of a polymer blend can be higher, equal to, or lower than that of the unadulterated parts.

4. Conclusions

In summary, the information of degradation and stability of polymer are crucial in order to ensure its practicability to be applied in various application can be enhanced. Therefore, the in-depth understanding of degradation mechanism of the polymeric under specific condition is beneficial the gain the information for further modification physical and chemical properties. However, obtaining data from experimental analysis in the effort to understand the fundamental understanding on degradation, durability and stability is still insufficient. Therefore, the requirement on theoretical study based on modelling and simulation would give the researcher a clear picture on the fundamental behind those arising issues. The exploration on the research regarding the improvement durability and stability properties of the polymers can be realized by adopting the nanotechnology aspect especially in self-healing polymer structures and integrity. This self-healing properties of polymer can open up a new versatility of the polymer material to be applied in various application where the half-life of the polymer either synthetic or bio-based polymer are becoming a critical factor for its commercialization.

Acknowledgement

The authors would like to acknowledge the financial support from the Ministry of Higher Education and Universiti Malaysia Pahang (UMP) with grant number RDU1803133.

References

[1] Cheng X Q, Wang Z X, Jiang X, Li T, Lau C H, Guo Z, Ma J and Shao L 2018 Towards sustainable ultrafast molecular-separation membranes: From conventional polymers to emerging materials *Progress in Materials Science* **92** 258-83

[2] Rezakazemi M, Sadrzadeh M and Matsuura T 2018 Thermally stable polymers for advanced high-performance gas separation membranes *Progress in Energy and Combustion Science* **66** 1-41

[3] Robeson L M 2016 Polymeric Membranes for Gas Separation *Reference Module in Materials Science and Materials Engineering*

[4] Sunarso J, Hashim S S, Lin Y S and Liu S M 2017 Membranes for helium recovery: An overview on the context, materials and future directions *Separation and Purification Technology* **176** 335-83

[5] Wang N, Wang L, Zhang R, Li J, Zhao C, Wu T and Ji S 2015 Highly stable "pore-filling" tubular composite membrane by self-crosslinkable hyperbranched polymers for toluene/n-heptane separation *Journal of Membrane Science* **474** 263-72

[6] Liu J, Hou X, Park H B and Lin H 2016 High-Performance Polymers for Membrane CO_2/N_2 Separation, Chemistry – A European Journal **22** 15980-90

[7] Sazali N, Salleh W N W, Ismail A F, Nordin N A H M, Ismail N H, Mohamed M A, Aziz F, Yusof N and Jaafar J 2018 Incorporation of thermally labile additives in carbon membrane development for superior gas permeation performance *Journal of Natural Gas Science and Engineering* **49** 376-84

[8] Sazali N, Salleh W N W, Ismail A F, Wong K C and Iwamoto Y 2018 Exploiting pyrolysis protocols on BTDA□TDI/MDI (P84) polyimide/nanocrystalline cellulose carbon membrane for gas separations *Journal of Applied Polymer Science*

[9] Mohamed M A, Salleh W N W, Jaafar J, Asri S E A M and Ismail A F 2015 Physicochemical properties of “green” nanocrystalline cellulose isolated from recycled newspaper *RSC Advances* **5** 29842-49

[10] Li P, Wang Z, Qiao Z, Liu Y, Cao X, Li W, Wang J and Wang S 2015 Recent developments in membranes for efficient hydrogen purification *Journal of Membrane Science* **495** 130-68

[11] Ogundare S A, Moodley V and van Zyl W E 2017 Nanocrystalline cellulose isolated from discarded cigarette filters *Carbohydrate polymers* **175** 273-281.

[12] Ilyas R A, Sapuan S M, Ishak M R 2018 Isolation and characterization of nanocrystalline cellulose from sugar palm fibres (Arenga Pinnata) *Carbohydrate polymers* **181** 1038-51

[13] Nowsheen G, Archana B L and Dhanjay J 2015 Biodegradable polymer blends: miscibility, physicochemical properties and biological response of scaffolds *Polymer International* **64** 1289-302

[14] Reddy M M, Vivekanandhan S, Misra M, Bhatia S K and Mohanty A K 2013 Biobased plastics and bionanocomposites: Current status and future opportunities *Progress in Polymer Science* **38** 1653-89

[15] Pandey J K, Reddy K R, Kumar A P and Singh R P 2005 An overview on the degradability of polymer nanocomposites *Polymer Degradation and Stability* **88** 234-50

[16] Kourde-Hanafi Y, Loulergue P, Szymczyk A, Van der Bruggen B, Nachtnebel M, Rabiller-Baudry M, Audic J L, Pölt P and Baddari K 2017 Influence of PVP content on degradation of PES/PVP membranes: Insights from characterization of membranes with controlled composition *Journal of Membrane Science* **533** 261-9

[17] Maya E M, Lozano A E, de Abajo J and de la Campa J G 2007 Chemical modification of copolyimides with bulky pendent groups: Effect of modification on solubility and thermal stability *Polymer Degradation and Stability* **92** 2294-99

[18] Collier A, Wang H, Yuan X Z, Zhang J and Wilkinson D P 2006 Degradation of polymer electrolyte membranes *International Journal of Hydrogen Energy* **31** 1838-54

[19] Zhang B, Li L, Wang C, Pang J, Zhang S, Jian X and Wang T 2015 Effect of membrane-casting parameters on the microstructure and gas permeation of carbon membranes *RSC Advances* **5** 60345-53

[20] Huertas R M, Tena A, Lozano A E, de Abajo J, de la Campa J G and Maya E M 2013 Thermal degradation of crosslinked copolyimide membranes to obtain productive gas separation membranes *Polymer Degradation and Stability* **98** 743-50

[21] Yun J, Chen L, Zhang X, Zhao H, Wen Z and Zhang C 2017 The effects of silicon and ferrocene on the char formation of modified novolac resin with high char yield *Polymer Degradation and Stability* **139** 97-106

[22] Garnier J, Dufils P E, Vinas J, Vanderveken Y, van Herk A and Lacroix-Desmazes P 2012 Synthesis of poly(vinylidene chloride)-based composite latexes by emulsion polymerization from epoxy functional seeds for improved thermal stability *Polymer Degradation and Stability* **97** 170-7

[23] Moharir R V and Kumar S 2018 Challenges Associated with Plastic Waste Disposal and Allied Microbial Routes for its Effective Degradation: A Comprehensive Review *Journal of Cleaner Production*

[24] Scaffaro R, Botta L, La Mantia F P, Gleria M, Bertani R, Samperi F and Scaltro G 2006 Effect of adding new phosphazene compounds to poly(butylene terephthalate)/polyamide blends. II: Effect of different polyamides on the properties of extruded samples *Polymer Degradation and Stability* **91** 2265-74

[25] Scaffaro R, Botta L, La Mantia F P, Magagnini P, Acierno D, Gleria M and Bertani R 2005 Effect of adding new phosphazene compounds to poly(butylene terephthalate)/polyamide blends. I: Preliminary study in a batch mixer *Polymer Degradation and Stability* **90** 234-43

[26] de Leon A C, Chen Q, Palaganas N B, Palaganas J O, Manapat J and Advincula R C 2016 High performance polymer nanocomposites for additive manufacturing applications *Reactive and Functional Polymers* **103** 141-55
[27] Laycock B, Nikolić M, Colwell J M, Gauthier E, Halley P, Bottle S and George G 2017 Lifetime prediction of biodegradable polymers *Progress in Polymer Science* **71** 144-89
[28] Lafyatis D S, Tung J and Foley H C 1991 Poly(furfuryl alcohol)-derived carbon molecular sieves: dependence of adsorptive properties on carbonization temperature, time, and poly(ethylene glycol) additives *Industrial & Engineering Chemistry Research* **30** 865-73
[29] Allen N S, Chirinis-Padron A and Henman T J 1985 The photo-stabilisation of polypropylene: A review *Polymer Degradation and Stability* 13 31-76
[30] Sionkowska A 2011 Current research on the blends of natural and synthetic polymers as new biomaterials: Review *Progress in Polymer Science* **36** 1254-76
[31] Alaerts L, Augustinus M and van Acker K 2018 Impact of Bio-Based Plastics on Current Recycling of Plastics *Sustainability* **10** 1487
[32] Nakajima H, Dijkstra P and Loos K 2017 The Recent Developments in Biobased Polymers toward General and Engineering Applications: Polymers that are Upgraded from Biodegradable Polymers, Analogous to Petroleum-Derived Polymers, and Newly Developed *Polymers* **9** 523
[33] Sadykov V A, Krasnov A V, Fedorova Y E, Lukashevich A I, Bespalko Y N, Eremeev N F, Skriabin P I, Valeev K R and Smorygo O L 2018 Novel nanocomposite materials for oxygen and hydrogen separation membranes *International Journal of Hydrogen Energy*
[34] Soares R M D, Siqueira N M, Prabhakaram M P and Ramakrishna S 2018 Electrospinning and electrospray of bio-based and natural polymers for biomaterials development *Materials Science and Engineering: C* **92** 969-82
[35] Kawaguchi H, Ogino C and Kondo A 2017 Microbial conversion of biomass into bio-based polymers *Bioresource Technology* **245** 1664-73
[36] Hu J, Wang Z, Lu Z, Chen C, Shi M, Wang J, Zhao E, Zeng K and Yang G 2017 Bio-based adenine-containing high performance polyimide *Polymer* **119** 59-65.
[37] Demirbaş A 2005 Recovery of Chemicals and Gasoline-Range Fuels from Plastic Wastes via Pyrolysis *Energy Sources* **27** (2005) 1313-1319.
[38] Hottle T A, Bilec M M and Landis A E 2013 Sustainability assessments of bio-based polymers *Polymer Degradation and Stability* **98** 1898-1907
[39] Tachibana Y, Yamahata M, Ichihara H and Kasuya K-i 2017 Biodegradability of polyesters comprising a bio-based monomer derived from furfural *Polymer Degradation and Stability* **146** 121-5
[40] Sazali N, Salleh W N W, Ismail A F, Kadirgama K, Othman F E C and N H Ismail 2018 Impact of stabilization environment and heating rates on P84 co-polyimide/nanocrystaline cellulose carbon membrane for hydrogen enrichment *International Journal of Hydrogen Energy*
[41] Sazali N, Salleh W N W, Ismail A F, Kadirgama K and Othman F E C 2018 P84 Co-Polyimide Based-Tubular Carbon Membrane: Effect of Heating Rates on Helium Separations *Solid State Phenomena* **280** 308-11
[42] Sazali N, Salleh W N W, Ismail A F, Ismail N H, Yusof N, Aziz F, Jaafar J and Kadirgama K 2018 Influence of intermediate layers in tubular carbon membrane for gas separation performance *International Journal of Hydrogen Energy*
[43] Sazali N, Salleh W N W, Ismail A F, Ismail N H, Mohamed M A, Nordin N A H M, Sokri M N M, Iwamoto Y and Honda S 2018 Enhanced gas separation performance using carbon membranes containing nanocrystalline cellulose and BTDA-TDI/MDI polyimide *Chemical Engineering Research and Design*
[44] Sazali N, Salleh W N W, Nordin N A H M and Ismail A F 2015 Matrimid-based carbon tubular membrane: Effect of carbonization environment *Journal of Industrial and Engineering Chemistry* **32** 167-71

[45] Sazali N, Salleh W N W and Ismail A F 2017 Carbon tubular membranes from nanocrystalline cellulose blended with P84 co-polyimide for H_2 and He separation *International Journal of Hydrogen Energy* **42** 9952-7
[46] Panda A K, Singh R K and Mishra D K 2010 Thermolysis of waste plastics to liquid fuel: A suitable method for plastic waste management and manufacture of value added products—A world prospective *Renewable and Sustainable Energy Reviews* **14** 233-48
[47] Achilias D S, Roupakias C, Megalokonomos P, Lappas A A and Antonakou E V 2007 Chemical recycling of plastic wastes made from polyethylene (LDPE and HDPE) and polypropylene (PP) *Journal of Hazardous Materials* **149** 536-42
[48] Marczewski M, Kamińska E, Marczewska H, Godek M, Rokicki G and Sokołowski J 2013 Catalytic decomposition of polystyrene: The role of acid and basic active centers *Applied Catalysis B: Environmental* **129** 236-46
[49] Zhang X, Lei H, Zhu L, Zhu X, Qian M, Yadavalli G, Wu J and Chen S 2016 Thermal behavior and kinetic study for catalytic co-pyrolysis of biomass with plastics *Bioresource Technology* **220** 233-8
[50] Lawrence J and Yamaguchi T 2008 The degradation mechanism of sulfonated poly(arylene ether sulfone)s in an oxidative environment *Journal of Membrane Science* **325** 633-40
[51] Klapiszewski L, Bula K, Sobczak M and Jesionowski T 2016 Influence of Processing Conditions on the Thermal Stability and Mechanical Properties of PP/Silica-Lignin Composites *International Journal of Polymer Science* **2016** 9
[52] Parcheta P, Koltsov I and Datta J 2018 Fully bio-based poly(propylene succinate) synthesis and investigation of thermal degradation kinetics with released gases analysis *Polymer Degradation and Stability* **151** 90-9
[53] Nisar J, Ali G, Ullah N, Awan I A, Iqbal M, Shah A, Sirajuddin, Sayed M, Mahmood T and Khan M S 2018 Pyrolysis of waste tire rubber: Influence of temperature on pyrolysates yield *Journal of Environmental Chemical Engineering* **6** 3469-73
[54] Li H, Jiang X, Cui H, Wang F, Zhang X, Yang L and Wang C 2015 Investigation on the co-pyrolysis of waste rubber/plastics blended with a stalk additive *Journal of Analytical and Applied Pyrolysis* **115** 37-42
[55] Miranda M, Pinto F, Gulyurtlu I and Cabrita I 2013 Pyrolysis of rubber tyre wastes: A kinetic study *Fuel* **103** 542-52
[56] Tan K, Li C, Meng H and Wang Z 2009 Preparation and characterization of thermoplastic elastomer of poly(vinyl chloride) and chlorinated waste rubber *Polymer Testing* **28** 2-7
[57] Yao Q and Wilkie C A 1999 Thermal degradation of blends of polystyrene and poly(sodium 4-styrenesulfonate) and the copolymer, poly(styrene-co-sodium 4-styrenesulfonate) *Polymer Degradation and Stability* **66** 379-84
[58] Naffakh M, Ellis G, Gómez M A and Marco C 1999 Thermal decomposition of technological polymer blends 1. Poly(aryl ether ether ketone) with a thermotropic liquid crystalline polymer *Polymer Degradation and Stability* **66** 405-13
[59] Snegirev A Y, Talalov V A, Stepanov V V, Korobeinichev O P, Gerasimov I E, Shmakov A G 2017 Autocatalysis in thermal decomposition of polymers *Polymer Degradation and Stability* **137** 151-61
[60] Hayes D G, Wadsworth L C, Sintim H Y, Flury M, English M, Schaeffer S and Saxton A M 2017 Effect of diverse weathering conditions on the physicochemical properties of biodegradable plastic mulches *Polymer Testing* **62** 454-67
[61] Ma C, Yu J, Wang B, Song Z, Xiang J, Hu S, Su S and Sun L 2016 Chemical recycling of brominated flame retarded plastics from e-waste for clean fuels production: A review *Renewable and Sustainable Energy Reviews* **61** 433-50
[62] Singh B and Sharma N 2008 Mechanistic implications of plastic degradation *Polymer Degradation and Stability* **93** 561-84

[63] Sazali N, Salleh W N W, Ismail A F, Kadirgama K, Othman F E C and Ismail N H 2018 Impact of stabilization environment and heating rates on P84 co-polyimide/nanocrystaline cellulose carbon membrane for hydrogen enrichment *International Journal of Hydrogen Energy*

[64] Rizzarelli P and Carroccio S 2014 Modern mass spectrometry in the characterization and degradation of biodegradable polymers *Analytica Chimica Acta* **808** 18-43

[65] Badia J D, Gil-Castell O and Ribes-Greus A 2017 Long-term properties and end-of-life of polymers from renewable resources *Polymer Degradation and Stability* **137** 35-57

[66] Sazali N, Salleh W N W, Ismail A F, Kadirgama K and Othman F E C 2018 P84 Co-Polyimide Based-Tubular Carbon Membrane: Effect of Heating Rates on Helium Separations *Solid State Phenomena* **280** 308-11

[67] La Mantia F P, Morreale M, Botta L, Mistretta M C, Ceraulo M and Scaffaro R 2017 Degradation of polymer blends: A brief review *Polymer Degradation and Stability* **145** 79-92

[68] Sazali N, Salleh W N W, Ismail A F, Wong K C and Iwamoto Y 2018 Exploiting pyrolysis protocols on BTDA□TDI/MDI (P84) polyimide/nanocrystalline cellulose carbon membrane for gas separations *Journal of Applied Polymer Science*