The Aging of Polymers under Electromagnetic Radiation

Subjects: Agricultural Engineering

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Polymeric materials degrade as they react with environmental conditions such as temperature, light, and humidity. Electromagnetic radiation from the Sun’s ultraviolet rays weakens the mechanical properties of polymers, causing them to degrade.

polymer degradation aging ultraviolet radiation composites

1. Introduction

Polymers are long-chain and giant molecules obtained from diverse smaller molecules known as monomers. Polymers are, therefore, composed of multiple repeating monomers in extended chains that can, at times, be branched or cross-linked [1]. White [2] explains that polymer aging refers to its change of chemical properties over time. Such properties that change include toughness and strength, density, and reactivity towards aggressive chemical substances [2]. Polymer aging can be attributed to either a physical change or chemical alterations when curing a thermoset. Exposing polymers to thermal conditioning fosters the deterioration of their chemical properties due to temperature increase [2]. The aging process of polymers when exposed to ultraviolet (UV) rays has been subject to extensive research interest. UV radiation is defined as a typology of non-ionizing radiation, which the Sun and other artificial sources like tanning beds emit [2]. For instance, Yousif and Haddad [3] mention that exposing polymers to UV radiation leads to photooxidative degradation, which is akin to breaking their chains, generating radicals, and lowering their molecular weight. This process results in the mechanical properties of the polymer deteriorating and waste generation after some unpredictable duration [3]. Therefore, exposing polymers to UV radiation enhances their aging by hastening the loss of their chemical as well as physical properties.

Nearly all the procedures of accelerated polymer aging use radiations generated by different lamps, like xenon, metal halides, fluorescent lighting tubes, and mercury, which help catalyze the process [4]. In agreement with this perspective, Frigione and Rodríguez-Prieto [5] argue that accelerated aging is possible as photo-chemical processes principally facilitate polymers’ degradation. In alignment, Pickett et al. [6] suggest that polymer aging degrading mechanisms occur when the irradiated plastic material relies on irradiation wavelengths, radiative energy, and its chemical structure. It is worth mentioning that the Earth receives UV radiations of the wavelength range 290–400 nm [4]. However, Frigione and Rodríguez-Prieto [5] suggest that devices capable of reproducing the Sun’s natural exposure on a polymer’s surface should use wavelength thresholds of 290–320 nm. These wavelengths are important to consider when deciding which range to employ to attain the best results for polymer aging.

One such thermal method for using UV radiation to foster a polymer's aging is chemiluminescence. This method, which is reported to have been in operation since the 1960s, entails using either photooxidation or thermal oxidation to emit weak light that is used to promote the aging of a polymer [7]. Kockott [7] suggests that a luminescent reaction terminates two peroxy radicals, leading to light emission by the excited carbonyl group when regaining its natural state. This process is especially prevalent in polyolefins' aging. In contrast to using thermal radiation to achieve the aging of a polymer, antioxidation has been suggested by Seguchi et al. [8] as the most suitable technique for polymer stabilization. The authors explain that antioxidation is useful in stabilizing most polymer materials, which reduces polymer degradation. **Figure 1** below shows a model for an antioxidative reaction with a polymer in a thermal environment.

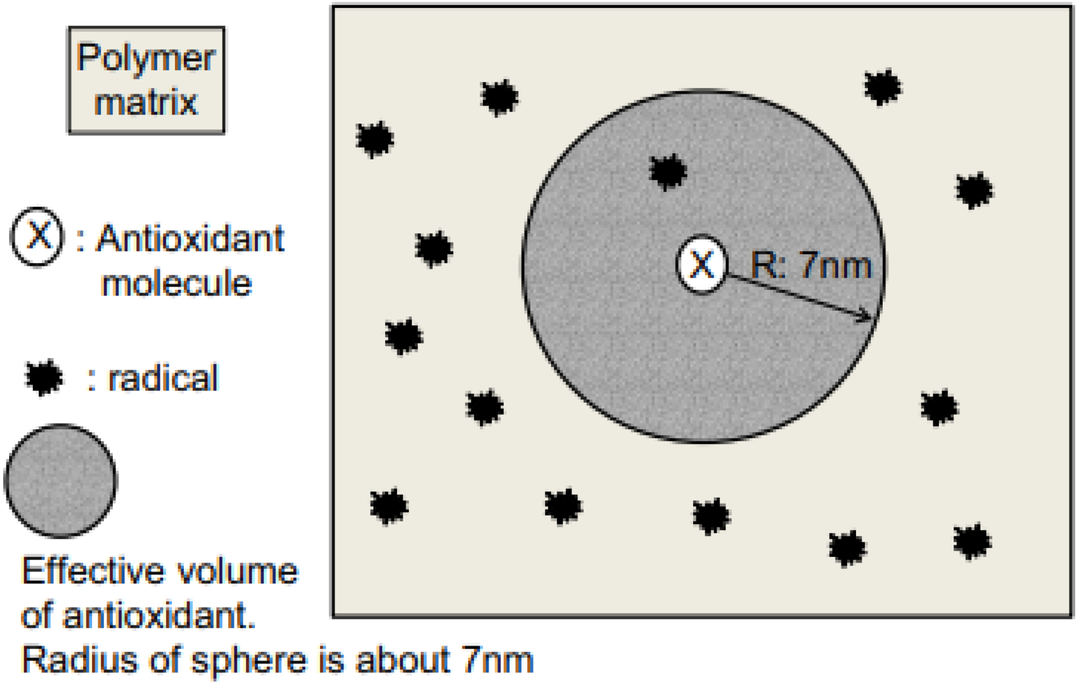

Figure 1. The interaction of an antioxidant with a polymer [8].

In **Figure 1**, the antioxidant depresses the production of radicals in the polymer matrix and effectively delocalizes energy for thermal activation. In this regard, a small proportion of an antioxidant is mixed with a polymer to stabilize it. Antioxidants help extend the lifetime of polymer materials, with diverse typologies adapted for use in different environments. In contrast, Seguchi et al. [8] contend that using oxidation schema can help create a chain reaction through the peroxy-radical as well as hydro-peroxide. In this mechanism, the polymers' antioxidant terminates free radicals and causes the hydro-peroxides of polymer chains to decompose as they undergo oxidation. However, using UV radiation to foster polymer aging can be dangerous as small particles are deposited into the surrounding ecosystems, leading to environmental degradation. This issue is prevalent since aged plastics have to be replaced, which leads to plastic pollution. For instance, according to Liu et al. [9], plastic debris exposed to UV radiation deforms and creates microplastics <5 mm in size. These particles can enter the surroundings by use of personal care products and plastic fabrication [9]. Therefore, aged plastic materials contribute to the degradation of the environment.

In terms of testing procedures, the lifespan of polymer materials and coatings increases over time, meaning elongated testing periods. However, much longer testing periods are unacceptable due to economic reasons [10][11]. In this regard, economic constraints have placed testing techniques under extreme pressure in a bid to reduce the durations for testing [12]. As such, Kockott [7] has suggested applying analytical methods in characterizing polymers' aging processes at molecular levels. Kockott [7] asserts that qualitatively altering the polymer at the macroscopic level is based on changing its molecular material level. As such, Kockott [7] suggests the need to identify analytical methods' molecular changes to enhance the determination of qualitative alterations before their detection at the macroscopic level. Essentially, this suggestion implies that testing periods can be shortened through analytical methods compared to measuring qualitative changes at the microscopic level. Polymer aging can also be accelerated by applying UV-A and UV-B lamps in laboratory tests. For instance, according to Fiorio et al. [13], UV-A aging contributes to a severe degradation of a polymer's irradiated surface (<100 μm), coupled with physical aging inducement. The surfaces exposed to UV-A get embrittled and visibly degrade, which influences the deterioration of ABS's mechanical properties [13][14]. Similarly, a study by Ma et al. [15], which examined the aging effect of UVB on concrete polymers, established that extreme changes in temperature and UV radiation led to the deterioration of the concrete's flexural performance as the aging time advances. Precisely, the findings indicate that for an equivalent aging period of four years, the polymer concrete deteriorated in terms of its flexural strength by 8.4% [15]. Hence, these radiations accelerate the aging process of polymers.

Examining polymer durability requires relatively shorter timeframes of about three years compared to their duration in service [15]. Thus, studies of polymer durability have attempted to accelerate the aging by raising their aging temperatures during experimentation. This feature is integral in ensuring that a polymer's loss of mechanical properties can be discerned within the duration of aging. After that, those measuring polymer durability are required to extrapolate the results from the extreme temperatures to service temperatures through the use of either empirical approaches or physical models [15]. However, the quality of such an extrapolation relies on manifold parameters like the number of degradation processes used, the potential couplings adopted, the homogeneity or heterogeneity of the degradation processes' character, and the range of temperatures used to accelerate aging. Keeping aging temperatures extremely high can influence different degradation processes, discernible from those in service [15][16]. In this regard, there is a trade-off between the used temperature range and aging times seen in polymer durability investigations. Baklan et al. [17] assert that the rate and grade of photodegradation rely on different factors like a polymer's chemical composition, the type of additives used, surface structure, and the prevalence of ultraviolet-sensitive molecules' functional groups. For instance, polymers have different chemical compositions, including hydroxyl groups, oxygen-containing elements, and carbonyl, which can influence their degradation rates and grades [16]. Concerning the types of additives, Baklan et al. [17] explain that photoactive additives like titanium oxide foster polymer degradation, while light stabilizers like HALS safeguard the polymer from UV radiation. As such, different mechanisms can be used to prolong the durability of polymers by shielding them from the adverse impact of UV radiation.

However, anti-aging components can be used to shield polymers from degradation. For instance, Moraczewski et al. [18] examined the possibility of modifying polycaprolactone using plant extracts to enhance its aging resistance. The findings suggest that natural extracts from coffee, cocoa, and cinnamon could be used to provide anti-aging components for biodegradable polymers [18]. The aging experimentation of these polymeric materials is usually conducted at elevated temperatures, coupled with high relative humidity as well as consistent exposure to ultraviolet radiation for extensive hours [18]. This argument concurs with the perspective of Kockott [10], who indicated that polymeric materials like plastics, varnishes, and textiles alter their chemical and physical properties based on the parameters to which they are exposed. Two crucial exposure parameters for the aging process of polymers include incidental solar radiation and the object's temperature [10]. As such, humidity and pollution from air and rain are not considered major parameters influencing the aging of polymers. Polymeric objects exposed to UV radiation absorb solar radiation, leading to the generation of free radicals, which initiates the degradation process and warming of the object relative to ambient temperatures [10]. Rodriguez et al. [19] concur with this assertion by arguing that as UV radiation interacts with polyolefins, it leads to photooxidative embrittlement, which is akin to random chain scission and cross-linking, and this ultimately influences a decline in the plastic's average molecular weight. These impacts suggest that polymeric materials degrade over time as they are used due to their interactions with UV radiation.

With increased applications of polymers in real-world scenarios, understanding the conditions that facilitate their aging and degradation is crucial in shaping their practical use. The aging and degradation of polymers have real-world implications in areas where they are applied, such as agricultural plastics. For instance, Cosnita et al. [20] suggest that it is crucial to understand waste polymer composites' stability vis-à-vis UV radiations, as there is a persistent increase in their outdoor applications. As these composite materials are prevalent in building materials, pavements, railway wall covers, carpeting railway crossings, and speed limiters' panel streets, understanding their resistance to UV radiation is important for practitioners since their context of use exposes them to solar radiation [20]. Ghosh et al. [21] underscore that there is a dearth of published literature regarding the aging of all waste composites on the basis of wood and tire rubber. These waste products are available in abundance, and they are non-biodegradable [21]. Therefore, converting them into value-added products presents the need for sustainable development to reduce the inherent environmental burden.

Exposing polymer composites to hydrothermal environments contributes to their faster degradation and inhibits their performance. Indeed, Qi et al. [22] report that polymer composites reinforced with carbon fiber undergo oxidation, softening and hydrolysis when exposed to hydrothermal environments, leading to reduced stiffness as well as strength. Furthermore, Qi et al. [22] suggest that exposing such polymer composites to hydrothermal settings accelerates the interfacial delamination between their fiber and matrix. This phenomenon induces the failure of the interface and the ultimate damage of the composite [22]. Zhumadilova et al. [23] agree with the latter assertion, claiming that the color and execution features of liquid thermal insulation coatings are influenced by the combined impacts of diverse climatic conditions. Such conditions include solar radiation, as well as changes in temperature, moisture, and precipitation, among others [23][24]. In this regard, understanding the thermal performance of polymer composites is integral in conceptualizing their life and reliability and enhancing their application in construction and civil engineering fields.

Short-term aging is capable of altering the mechanical properties and morphological elements of polymers, especially those modified through bitumen, recycled plastic materials, and other wastes. This perspective is highlighted by Celauro et al. [25], who argue that bitumen that has been modified with polymers to offer enhanced performance is affected by the short-term degradation of polymer composites resulting from the high processing temperatures to which they are exposed. The same scenario occurs when modified binders are produced as the polymeric material is dispersed under extreme heat in the mass of the bitumen [25]. In concurrence, Zhu et al. [26] conducted a study to determine the impact of the polymer structure on modified binders' physicochemical features and performance-related properties. The study also considered the influence of polymer content as well as aging conditions on the modified asphalt binders' performance [26]. Through a polynomial experimental design, the study established that binder properties are impacted by both the polymer structure and the interaction between polymer content, structure, and aging [26]. For instance, polymer structure is integral in predominantly influencing the morphology of polymer particles in modified binders and fostering the stability of their storage [26]. Polymer content affects the polymeric feature peaks in the spectrum of infrared, elasticity, and elastic recovery, as well as the binders' non-recoverable creep compliance. The aging condition of polymeric materials influences their variations in the oxidization of binders and their complex shear modulus [26][27]. As such, the polymer's structural impacts are limited when the polymer content is low, while high polymer content substantially influences observable property differences.

2. The Effect of Polymer Aging in Real-World Applications and Agricultural Plastics

Polymers are used in different industries ranging from construction to everyday applications, such as through the use of plastics for packaging substances and agricultural applications in erecting greenhouse structures. For instance, 3D polymers have also been increasingly used in real-world applications in contemporary industries [28][29][30][31][32][33]. **Figure 2** below shows the change in tensile conditions of a flour/PLA composite after consistent exposure to UV radiation.

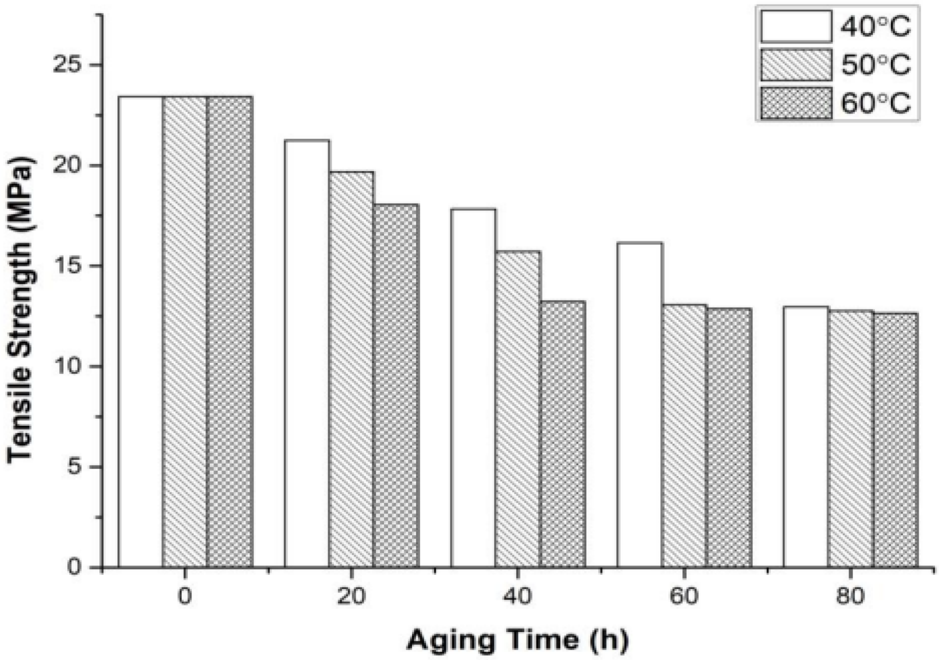

Figure 2. Change in tensile strength of flour/PLA composite after UV aging exposure (source: Lin et al. [31]).

Based on **Figure 2** above, the tensile strength of the initial flour/PLA polymer composite declines after exposure to UV radiation. The legend for temperature ranges shows that group 3 filaments had the highest thermal heating conditions, with 60 °C, and they stabilized at 40 h (**Figure 2**). At thermal conditions of 50 and 40 °C, the tensile strength of the polymer composite stabilized after being treated for 60 and 80 h, respectively. In that regard, a rise in the aging temperatures led to an increase in the aging process of the polymer. As an illustration, polymer concretes, whose binders are made of polymeric materials instead of cement, are one such area where 3D polymers are used in real life [34]. House et al. [35] note that although 3D printing is linked to the development of asthmatic conditions, it is one of the novel technologies that generate three-dimensional images from digital files by depositing and integrating plastic materials with others like metals and ceramics through additive manufacturing. Polymer concretes have been used continuously across different areas of applications, including making precast architectural facades, wastewater pipes, manholes, and bridge deck overlays, among others [34]. In comparison to traditional Portland cement concrete, polymer concretes have elevated tensile strengths, better bond strengths, and enhanced durability [35]. Bedi et al. [36] note that although more costly than conventional concrete, polymer concrete is reputed to possess an enhanced microstructure, which offers it better durability. Krčma et al. [37] and Furet et al. [38] explain that to create 3D polymer concrete, aggregates, polymer resin, and fillers are mixed with a substituted cement binder. The resulting polymer concrete can thus be used in 3D printing, wherein the stability of the shape is a vital feature. Kozicki et al. [39] mention that 3D dosimeters contain compounds that undergo changes under the effects of ionizing radiation. Chapiro [40], Lebedev and Startsev [41], and Davenas et al. [42] suggest that ionizing radiation influences material aging because its features bring about this change, which is evident in polymers as well as polymer composite materials. In this regard, polymer composite materials have thermoplastic coupled with thermoset matrices that possess glass, carbon, and carbon reinforcements, among other fibers that degrade once exposed to ionization radiation sources [35][43]. However, contrastive evidence from Hakamivala et al. [44] suggests that the integration of individual as well as interactive parameters of 3D printing, like layer thickness, delay duration, and printing orientation, can enhance the scaffolding mechanical features as well as the dimensional error. Integrating these multiple printing parameters into the 3D printing process enhances polymeric materials' resistance to degradation and aging. For instance, the results from the study's Response Surface Methodology reiterate that increasing the 3D printing process delay time leads to enhanced binder spreading coupled with uniformity [44]. This outcome is accompanied by the better compression strength of polymeric materials. Moreover, increasing delay time ensures that the binder spreads more vertically, thus generating increased dimensional errors in the Z-direction [44]. Thus, applying the Response Surface Methodology offers a timely and cost-effective design for printing prototypes with enhanced polymer strength as well as dimensional errors.

However, polymer aging impacts the performance and stability of polymeric materials in their real-life applications. In a study by Sun et al. [45], the oxidation and degradation of high-viscosity modified asphalt were examined through gel permeation chromatography to determine the aging and stability features. According to Sun et al. [45] and Lin et al. [46], asphalt plays an important role in constructing pavements; however, the longevity of infrastructures made from this polymeric material degrades faster due to aging. Findings from Sun et al. [45]

indicate that extending the proportion of large molecules and decreasing the proportion of polymer weight helps characterize polymeric materials' oxidation and degradation levels, respectively. Indeed, Makki et al. [47] underscored that the oxidation and polymer degradation degrees for high-viscosity modified asphalt rise as it ages and weathers at its apex. On the other hand, Lin et al. [46] suggested that combining modified asphalt mixtures with fibers can enhance the porosity of pavement construction owing to their superior stability and anti-aging properties. In that regard, Lin et al. [46] reported that polyester fibers combined with asphalt mixtures can show enhanced performance against raveling and fatigue, as well as resisting the rutting and cracking of pavements constructed using these materials. However, such resistance and enhanced performance features were limited when lignin fibers were added to the asphalt mixtures. Both polyester and lignin exhibit improved stability against short-term and long-term aging. The results from the Fourier Transform Infrared Spectroscopy analysis show that adding fiber to bitumen does not yield substantial impacts on its oxidation or deterioration [46]. High-Content SBS Polymer-Modified Bitumen has exceptional features enabling it to develop a masking effect in its original state, thus concealing the impacts of fiber enhancement [45][46][47]. After extensive aging, this impact becomes profound. Thus, Lin et al. [46] recommend that the assessment and design of the performance of high-content SBS polymer-modified bitumen should be determined by post-aging functioning. Likewise, Desidery and Lanotte [48] examined the effects of modifying polymeric materials with asphalt binders on their chemical, thermal as well as microstructural elements. The experimental findings of the study reveal that undisclosed crystalline modifiers had significant effects on the microstructure of asphalt binders [48]. This impact was not established when styrene–butadiene–styrene (SBS) thermoplastic elastomers were used to modify the microstructure [48]. Therefore, polymeric materials' aging processes impact the features of the base bitumen, undisclosed crystalline modifiers, and SBS. Hu et al. [49] contend that new materials like light-absorbing materials, antioxidants, and light-shielding materials can be uniquely combined and optimized to yield enhanced anti-weather aging for asphalt polymers. Combining these three materials can help improve the high-content polymer-modified asphalt's anti-aging properties by absorbing UV radiation, shielding it, and neutralizing free radicals [49]. In support, Goncalves Bardi et al. [50] assert that polymerization reactions are used in curing blend substrates, which entails converting reactive formulations into highly cross-linked films, resulting in the creation of a 3D network capable of resisting external degradation factors because physical–chemical reactions cannot undo it. Consequently, this anti-aging property is crucial in preventing polar oxygen-containing functional groups from forming, as well as preventing the deterioration of polymer molecules when exposed to extreme weather conditions.

Polymeric materials are also used in agriculture to promote crop productivity. In greenhouses, plastics are used to increase crop yield by shielding plants from adverse weather conditions. **Figure 3** below shows a greenhouse using plastics to regulate the amount of light penetrating for crop production.

Figure 3. Illustration of greenhouse use of plastics [51].

UV radiations of the size 200–400 nm can harm plant growth [51]. In contrast, plant growth is promoted by blue-violet and red-orange light, which is made possible through the conversion of UV radiations in greenhouses. In concurrence, Vijayalakshmi et al. [52] argue that plastic greenhouses are a typical application of polymers in agriculture as they help convert harsh UV radiations to bluish-violet light of between 400 and 480 nm and reddish-orange light of between 600 and 700 nm. These plastic materials are able to absorb a portion of the light spectrum generated by the Sun and convert it into the needed light spectrum to increase agricultural productivity. Higher UV radiation wavelengths are scarcely absorbed by chlorophyll. As such, plastic greenhouses show extensive application in cold climates to convert UV photons to bluish-violet and reddish-orange light, which is vital in using electromagnetic energy in cultivating plants [52]. Research into this area by Wang et al. [51] suggests that single-light agricultural films can be used to regulate infrared light in greenhouses. In their study, Wang et al. [51] created a composite coating of waterborne polyurethane (WPU) to convert light and bar light for greenhouse films, thus underscoring how polymers are used in greenhouse production to promote a rise in crop yield. In this regard, polymeric materials can be utilized as radiation conversion materials to convert UV radiations to favorable light that promotes plant growth. In contrast, Al-Helal et al. [53] suggested that under intense climatic conditions, plastic-covered greenhouses lose their optimal properties very quickly due to aging, leading to a damaged orientation and shape. It is worth emphasizing that the degradation rate of greenhouse plastics depends on the surface location as well as the underlying orientation of the cover [53][54]. Thus, the degradation of greenhouse plastics impacts the longevity of use in arid climate conditions due to high temperatures that denature their amorphous features.

Different soil and humidity conditions influence the accelerated aging of agricultural microplastics differently. A study by Bonyadinejad et al. [55] examined the phenomenon of the photodegradation of microplastics used in agricultural production after their accelerated use to determine aging when exposed to environmental conditions. The photodegradation behavior of low-density polyethylene (LDPE) microplastics was studied via accelerated UVA radiation experimentations under varying conditions of relative humidity as well as soil deposition [55]. Two humidity conditions of RH10 and RH70 were used in that experiment, while the degree of UV radiation with long wavelengths (UVA) was calculated through the spectral quantum yield [55]. The findings underscored that LDPE products with a lower molecular weight of Mw = 233 kD underwent greater photodegradation than heavier ones with Mw = 515 kD [55]. High humidity constrains microplastics' photooxidation process and reduces surface changes in these polymeric materials [56][57][58][59][60][61][62][63][64][65]. However, soil particles' deposition impacts microplastics' photodegradation behavior [55][64]. As such, microplastics covered by soil particles do not experience degradation, as opposed to those deposited near soil particles [55][62]. Hence, covering microplastics with soil particles is integral in extending their lifespans for agricultural use. Indeed, an experiment conducted by Amin et al. [59] on the effect of poly-starch N on the natural weathering of LDPE indicated that when these two components are blended, the matrix reduces the tensile properties and extent of crystallinity of the polymer. Increasing the proportion of poly-starch N in the blend heightens the decline of the polymer's tensile properties [59]. However, Amin et al. [59] demonstrated that exposing the blends to natural weathering processes and increasing the volume of Polystarch N in the mix exacerbates natural degradation, as revealed by the scanning electron microscope tests that were conducted. Thus, blending LDPE with Polystarch N increases polymer degradation and aging.

Furthermore, agrochemicals also accelerate the aging process of plastics used in agriculture. For instance, findings from Picuno et al. [66] and Schettini et al. [67] have also demonstrated that when exposed to varying agrochemicals like anti-aphid or fungicides and aged artificially for distinct periods, agricultural plastic film is contaminated and its lifespan reduced. In this regard, agrochemicals considerably impact plastic films by worsening their aging processes and rapidly reducing their mechanical properties, thereby reducing their lifespans by above 50% relative to virgin plastic [66][67]. This aging phenomenon of polymers used in agriculture has twofold impacts, lowering the plastic films' working age and reducing their potential transformation into closed-loop recycled materials after entry into the recycling stage [62][68]. Indeed, when these plastic films interact with agrochemicals, they tend to degrade faster, as confirmed by the rise in the number of detected carbonyl indexes (CI) [66]. This aspect suggests the impossibility of recycling plastic film that has come into contact with agrochemicals during its useful working life [66]. Nevertheless, high thermal conditions, humidity, and the addition of impurities such as agrochemicals accelerate the aging of LDPE polymers used in greenhouse applications [69]. For instance, Dehb et al. [70] and Dehb et al. [71] underscored that the degradation of carboxyl groups in many polymers requires extensive exposure to a UV irradiation source for their aging to be observed during field studies and laboratory tests. LDPE degradation was one of the polymers reviewed in this study concerning its degradation and aging process, and the findings suggested that it deteriorates once exposed to a UV radiation source for extensive hours [72]. Electromagnetic sources with wavelengths ranging between 300 and 400 nm could influence the generation and breakage of the bonds between polymer molecules [73][74]. Free radicals are produced in the polymer as the wavelength of electromagnetic radiation increases towards the 400 nm threshold [75]. The adverse effects of plastic material aging on the generation of secondary materials like anthocyanins and total phenolics that degrade the surroundings have also been covered by Katsoulas et al. [76] as one of the elements of pure polythene used for blocking UV radiation in greenhouses. Thus, the aging effect of polymers is experienced by farmers employing greenhouses to increase crop yield, as the adverse thermooxidative conditions contribute to the aging of plastic materials employed.

Polymers are also used in other large-scale industrial uses. For large-scale industrial applications, Al-Salem et al. [77], Feldman [78], and Andrady et al. [79] argue that fillers and reinforced polyolefin (PO) polymers have diverse applications, including in traditional wood fibers, construction, polyesters, and short glass production, and their contemporary uses continue to rise. Some of the contemporary applications include engineering disciplines and customized use areas like protection surfaces and insulators [53][69][80]. However, accelerated weathering tests conducted by Al-Salem et al. [81] on linear low-density polyethylene (LLDPE) blended with plastic films confirmed that extreme temperatures degrade them faster, as polyolefin polymers lose their amorphous region once exposed to UV radiation. UV radiation deteriorates plastic waste components, accelerating their rate of aging [82][83][84]. Likewise, previous research by Ávila-López et al. [85] and Cacuro et al. [86] acknowledged that many polymeric materials are vulnerable to UV radiation because the overall energy of UV radiation supersedes the strength of the inherent carbon bonds in polymers. Concurrent perspectives from Garg et al. [87], Lei et al. [88], and Palkar et al. [89] indicate that electromagnetic radiation from a UV source can fracture a polymer and reduce its molecular weight, leading to the generation of free radicals. Moreover, Cheng et al. [90] and Fraga Dominguez et al. [91] suggested that polymer irradiation from a UV source can lead to an increase in the molecular chain length coupled with its cross-linking. However, Rivas Aiello et al. [92] and Tian et al. [93] underscored that different polymeric materials may need exposure to different aging conditions to facilitate the degradation and deterioration of their mechanical properties. In contrast, studies by Xiu et al. [94] and Zhou et al. [95] have illustrated that titanium dioxide (TiO_2) can be added to Polylactide (PLA) to enhance its UV resistance for outdoor applications. In concurrence, Smith et al. [96] have suggested the use of Porosity Induced Side chain Adsorption (PISA) as a pathway for enhancing super-glassy polymers' stability against physical aging by using the porous aromatic framework PAF-1 to improve the void space, enhance gas transport speed and freeze glass polymers in a state of low density. Likewise, El-Hiti et al. [97] suggest the addition of UV absorbers such as polyphosphates, organometallic complexes and Schiff bases as plastic photostabilizers to provide a mechanism for modifying polymeric materials' resistance to aging. Furthermore, to circumvent the photodegradation of polymeric materials' mechanistic complexities, Zemke et al. [98], Auras et al. [99], Wallnöfer-Ogris et al. [100], Karlsson and Albertsson [101], He et al. [102], Ray and Cooney [103] and La Mantia et al. [104] have suggested the use polymers that possess metal–metal bonds integrated into their backbone. Irradiating these materials breaks the metal–metal bonds, followed by their radicals being trapped by a suitable radical trap like molecular oxygen or the bond between carbon and chlorine molecules [98]. This phenomenon leads to the creation of a net backbone cleavage, which deters photodegradation [98]. In this regard, there are different methods through which plastics used in agricultural applications can be made to last longer.

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