

A Review of Degradation and Life Prediction of Polyethylene

Yang Wang ¹, Guowei Feng ¹, Nan Lin ^{2,*}, Huiqing Lan ³, Qiang Li ⁴, Dichang Yao ⁵ and Jing Tang ⁶¹ School of Mechanical Engineering, Xinjiang University, Urumqi 830046, China² Pressure Pipe Department, China Special Equipment Inspection and Research Institute, Beijing 100013, China³ Laboratory of Vehicle Advanced Manufacturing, Measuring and Control Technology (Ministry of Education), Beijing 100044, China⁴ Xinjiang Uygur Autonomous Region Inspection Institute of Special Equipment, Urumqi 830000, China⁵ Xinjiang Agricultural Machinery Quality Supervision and Management Station, Urumqi 830054, China⁶ International Cultural Exchange College, Xinjiang University, Urumqi 830046, China

* Correspondence: sy_linnan@163.com

Abstract: After around 50 years of development, the key substance known as polyethylene has been extremely influential in a variety of industries. This paper investigates how polyethylene materials have been used in the domains of water, packaging, and medicine to advance contemporary society in order to comprehend the physical and chemical alterations that polyethylene undergoes after being subjected to long-term environmental variables (e.g., temperature, light, pressure, microbiological factors, etc.). For the safe operation of polyethylene materials, it has always been of the utmost importance to evaluate polyethylene's service life effectively. This paper reviews some of the most common literature journals on the influence of environmental factors on the degradation process of polyethylene materials and describes methods for predicting the lifetime of degradable polyethylene materials using accelerated aging tests. The Arrhenius equation, the Ozawa–Flynn–Wall (OFW) method, the Friedman method, the Coats–Redfern method, the Kissinger method and Kissinger–Akahira–Sunose (KAS) method, Augis and Bennett's method, and Advanced Isoconversional methods are all discussed, as well as the future development of polyethylene.

Keywords: polyethylene; degradation; kinetic models; thermal analysis; life prediction



Citation: Wang, Y.; Feng, G.; Lin, N.; Lan, H.; Li, Q.; Yao, D.; Tang, J. A Review of Degradation and Life Prediction of Polyethylene. *Appl. Sci.* **2023**, *13*, 3045. <https://doi.org/10.3390/app13053045>

Academic Editor: Theodore E. Matikas

Received: 15 February 2023

Revised: 23 February 2023

Accepted: 25 February 2023

Published: 27 February 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Polyethylene is one of the most significant and useful polymers that has been extensively studied for use as a plastic material [1–8]. The benefits of using polyethylene as a commercial plastic material include its excellent mechanical properties, good flexibility, good chemical resistance, lightweight properties, good thermal stability, and high-cost performance [9,10]. The piping sector has been impacted by the trend of replacing steel with plastic during the past few decades, resulting in the steady replacement of metal-based pipes with plastic pipes. Polyethylene pipes are the most commonly utilized among them [11,12]. Consider the case of high-density polyethylene pipes. Its market worth was USD 15.975 billion in 2018, and 9.283 million tons were consumed each year. The service life of polyethylene pipes will not be less than 50 years, and it will continue to grow at a rate of at least 5% annually in the upcoming years [13,14].

Polyethylene has numerous applications in a wide range of industries, including agriculture [15], manufacturing [16,17], medicine [18–20], construction [21,22], packaging [23], energy [24], outdoor items [25], and others, due to its technical benefits and low cost when compared to other materials. In China alone, the use of agricultural films reached 2.6 million tons in 2016, including 1.47 million tons of polyethylene films, covering 18.4 million hectares of land [26].

Although polyethylene materials offer great resistance to microbial, peroxide, and degrading damage, they do have a tendency to alter their initial performance characteristics

with time [27–30]. In general, three frequent and significant occurrences are bound to happen when polyethylene is present in a gaseous or liquid environment for an extended period of time. The first phenomenon demonstrates that the mobility of polyethylene molecules is altered by the diffusion of gas or liquid molecules, just as it is by changes in temperature, pressure, or time, which also have an impact on the material's mechanical properties. The second phenomenon relates to the fact that, due to the extremely adhesive nature of the amorphous phase attached to the crystalline skeleton, the physical aging of polyethylene materials is destined to occur over extended periods in glassy amorphous polymers or semi-crystalline polymers [31,32]. The third phenomenon demonstrates that polyethylene is subject to aging and degradation processes when exposed to chemically active gases or liquids for extended periods. As a result, brittleness [33], fracture [34], bending [35], and other phenomena may occur, which may shorten the service life of polyethylene products.

In general, it's critical to comprehend the mechanisms of degradation in addition to the elements that influence how polyethylene materials deteriorate over time. Researchers must investigate polyethylene's deterioration behavior and offer theoretical backing to enhance the material's performance and service life. However, there has not been a study conducted yet that completely explains the degradation mechanism of polyethylene.

The aging degradation process of polymeric materials is described in this work as being influenced by several common external environmental conditions. First, it enumerates the common ways that polyethylene degrades in the environment and describes the effects that these different elements have on the process. Second, illustrations of the fundamental hypotheses and technical approaches employed in the experimental research carried out thus far are provided. Finally, some thoughts and views are shared along with predictions about polyethylene's future trends.

2. Aging Degradation of Polyethylene

2.1. The Process of Degradation

Catalytic peroxide decomposition, direct interactions of metal compounds with organic substrates, oxidation, and energy transfer during photolysis are the primary mechanisms of the chemical degradation of polymers [36]. While the chemical structure of a polymer frequently does not change much, polymer degradation involves a reduction in the polymer's molecular weight [37]. A macromolecular complex called a polymer is made up of big molecules with repeating structural elements. Polymers are typically combinations of substances with various chain lengths or substances with various molecular weights. The properties of polymers are strongly affected by their molecular weight, and this is also one of the processes through which macromolecular substances are created [38].

The primary source of the polymer degradation process is the continuous interaction between oxygen and the polymer's macromolecules, as well as free radicals created as a consequence of environmental factors such as temperature, humidity, light, mechanical stress, and radiation [39]. In addition, it appears to suggest a decrease in molecular weight, potential branching, and, in a few cases, the formation of cross-linked structures [40]. The unstable oxidized substances formed by degradation gradually converge towards the formation of stable macromolecules with oxidation groups and cause significant changes in the molecular structure, such as molecular weight, polydispersity, branching, etc. While other polymers often migrate in the direction of lower molecular weights, the development of cross-linked structures as mentioned above occurs primarily in the degradation of polyethylene.

For polyethylene materials, aging is bound to occur with extended use. Both aging and degradation can have a significant impact on the performance of polyethylene. Exposure to numerous environmental variables, such as heat, UV radiation, ozone, chemical attack, mechanical stress, and microbes, can cause polyethylene to degrade, eventually resulting in embrittlement, cracking, discoloration, etc. [41,42]. Understanding the primary stages of polyethylene breakdown is crucial for this reason.

2.2. Types of Degradation

Premature failure of polyethylene materials is caused by irreversible chemical reactions or physical alterations. Abiotic and biodegradation are the two categories into which polyethylene degrades. Biodegradation is the term used to describe the degradation caused by the action of microorganisms that alter and consume polyethylene and change its properties. Abiotic degradation is defined as deterioration caused by external environmental variables, such as temperature and UV irradiation. Even though each of these two degradation mechanisms can be used to classify the deterioration of polyethylene, the two types work together in nature [43].

2.2.1. Biodegradation

The process of biodegradation happens when microbial populations, other decomposing organisms, or abiotic forces work together to break down biodegradable materials into minute parts [44]. Three primary processes make up the biodegradation of polyethylene: (1) biodegradation, which occurs when microorganisms grow on the polyethylene's surface or within it, altering its mechanical, physical, and chemical qualities; (2) biodegradation, which is the process of having microorganisms break down a polymer into oligomers and monomers; (3) assimilation, which is the process by which microbes acquire the requisite carbon, energy, and nutrients from the breakdown of polymers and transform the carbon in the material into carbon dioxide, water, and biologically necessary chemicals [45]. The chemical composition, molecular weight, and crystallinity of the polymer, as well as other physical, chemical, and biological aspects, all affect how effectively a substance degrades [46].

Biological factors that may cause the biodegradation of polyethylene include bacteria, fungi, and microorganisms. Over the past few decades, numerous bacterial strains have been found to interact with polyethylene, and research studies have shown that there are already several genera of bacteria and a small number of genera of fungus that are able to degrade polyethylene. Some of the categories are shown in Table 1. In reality, enzymes choose particular functional groups. Generally, shorter chains, more amorphous parts, and less complicated structures in polymers make them more susceptible to microbial biodegradation [47].

Table 1. Bacterial and fungal strains linked to polyethylene biodegradation [48].

<i>Fungiidae</i>	<i>Fungal Species</i>	<i>Bacteriaceae</i>	<i>Bacterial Species</i>
<i>Penicillium</i>	<i>Simplicissimum</i> <i>Frequentans</i> <i>Pinophilum</i>	<i>Bacillus</i>	<i>Amyloliquefaciens</i> <i>Brevies</i> <i>Cereus</i>
<i>Aspergillus</i>	<i>Versicolor</i> <i>Flavus</i>	<i>Streptomyces</i>	<i>Badius</i> <i>Viridosporus</i>
<i>Phanerochaete</i>	<i>Chrysosporium</i>	<i>Rahnella</i>	<i>Aquatilis</i>
<i>Verticillium</i>	<i>Lecanii</i>	<i>Rhodococcus</i>	<i>Rhodochrous</i>
<i>Cladosporium</i>	<i>Cladosporioides</i>	<i>Brevibacillus</i>	<i>Borstelensis</i>

2.2.2. Non-Biodegradable

The abiotic degradation of polyethylene is influenced by environmental and molecular factors. The breakdown of polyethylene is promoted and accelerated by environmental elements such as sunlight's UV radiation, oxygen, heat, water, certain animals, and contaminants. The combined action of these factors may have a synergistic effect on the degradation rate of polyethylene [49]. Photoreactions and thermal oxidation reactions, which result in the creation of new products during chain breakage, hydrogen atom detachment, or cage effects, are the main environmental drivers of polymer degradation [50].

The interaction between oxygen and UV light causes polyethylene to begin to photodegrade. While photodegradation is the process by which molecules produce free radicals, photooxidation is the process by which polymers are destroyed by absorbing photons of visible,

ultraviolet, or infrared light in the presence of oxygen [51]. Random chain breakage and photooxidation are the primary outcomes of photodegradation, and these processes in turn cause secondary crystallization and the creation of several degradation products, including carboxylic acids, ketones, and aldehydes, which are collectively known as carbonyl compounds [52,53]. The Norrish reaction can result in the synthesis of vinyl groups (such as unsaturated bonds and conjugated systems), and it is crucial to realize that hydroperoxides are byproducts of the free radical formation process [54]. In addition to the breakdown of hydrogen peroxide, Norrish types I and II processes involving ketone groups can also start the photooxidation of polyethylene [55], as shown in Figures 1 and 2. Chain breakage and cross-linking are the primary and secondary outcomes of these three starting processes, respectively.

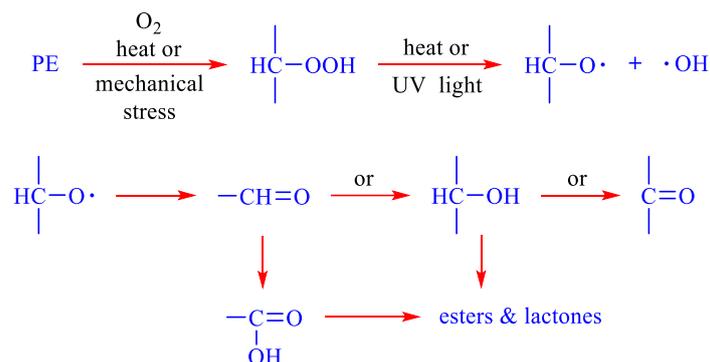


Figure 1. Polyethylene breakdown products are depicted schematically [56].

Norrish I



Norrish II



Figure 2. Two types of Norrish reaction [57].

The process by which heat or high temperatures are applied to a material, product, or component and where the outcome is a loss of physical, chemical, or electrical qualities is referred to as “thermal degradation” [58]. Free radical chains that are engaged in thermal and photodegradation have fundamentally identical processes. Typically, the degree to which the reaction with oxygen takes place has a significant impact on the mechanism and rate of degradation. The molecular amplification reactions are mostly chain-breaking reactions when oxygen is present [47]. Depending on the physical and chemical makeup of the polymer, for which many thermal degradation mechanisms exist, thermal degradation may cause molecular deterioration. The most frequent is the polymer’s intermolecular links being broken or unchained, releasing oligomers and monomer units. Some polymer backbone and side chain reactions will also contribute to the polymer’s final decomposition [59].

One of the crucial components of abiotic degradation’s parameters is chemical degradation. The characteristics of polyethylene macromolecules may change as a result of reactions with atmospheric contaminants and some agrochemicals. Many materials must come into contact with air when used in daily life, making reactions with oxygen in the air simple. Free radicals are created when the covalent bonds in polyethylene react with the oxygen molecules in the air. The covalent bonds of polyethylene are subject to oxidative degradation, which is dependent on the chain structure of polyethylene and works in conjunction with photodegradation to form free radicals. Peroxyl radicals from oxidative

degradation can also act on polyethylene and cause cross-linking or chain breakage, just like the byproducts of the Norrish reaction stated above. Another process that might lead to the chemical breakdown of polymers is hydrolysis reaction [60–62]. It is significant to note that because polyethylene molecules are entirely composed of alkyl groups and lack any radical energy groups that could interact with water molecules, they cannot be hydrolyzed.

As the name suggests, catalytic degradation refers to the use of catalysts to break down polyethylene. Typically, catalytic degradation is employed in scientific research or to degrade polyethylene materials. The use of an appropriate catalyst and optimal processing conditions might result in the development of the intended, more precise product, and, in some situations, prevent the formation of inferior products, giving catalytic degradation some advantages over the other degrading methods previously discussed [63]. The ability to shorten experiment durations and lower reaction temperatures during studies is a more significant benefit of catalytic degradation.

Polyethylene experiences mechanical degradation most frequently as a result of the influence of various stresses on the material. These forces can occur for a variety of reasons. For example, buried polyethylene pipes may experience operational issues during installation, and wild animals may unintentionally harm them as a result of the pressure that the soil and carried material exert on them [45]. This also applies to polyethylene products used outside, such as mulch film and protective jackets used on some cables, which may experience multiple mechanical degradations under unforeseen outdoor conditions [64–66]. In general, damage to polyethylene materials caused by macroscale factors, including soil or water pressure, may not be immediately noticeable but may start to have an impact at the microscopic molecule level. Even though mechanical causes are not the primary cause of degradation, once a material has been mechanically traumatized, it may be more susceptible to the effects of biodegradation [59]. Under field circumstances, mechanical forces and other abiotic parameters (such as humidity, radiation, and contaminating substances) interact with polyethylene material.

2.3. General Mechanism of Degradation

Various types of polymers have different degradation mechanisms. The deterioration of polymeric materials may involve multiple degradation pathways at once [67]. Bond fractures in the polymer's backbone are the main method by which they degrade, and these breaks can occur anywhere in the chain or at the ends of the chain due to random generation. A frequently used mechanism in the breakdown of polymers is the chain-break decomposition mechanism. A multi-step free radical chain reaction with the general properties of such reaction mechanisms as initiation, proliferation, branching, and termination is involved in the chain-breaking breakdown process [68].

Free radicals are produced in both induced reactions—when a chain break happens at a random location in the main chain—and the terminal chain breaks reactions, where such a tiny unit or group is broken at the end of the main chain [59]. The following is the reaction sequence:



The proliferative process begins with a free radical reaction with oxygen molecules, then produces a peroxide radical, a hydroperoxide group with hydrogen atoms, and finally, a peroxide radical with oxygen molecules [69]. The resulting groups are extremely unstable and readily decompose into renewable free radicals. The following is the reaction sequence:





Taking over a hydrogen atom or another atom on a carbon atom next to a radical from another chain is known as a “termination reaction”. The following is the reaction sequence:



Both biotic and abiotic circumstances, such as photooxygenation, can cause the aforementioned degradation pathways to occur in polymeric materials. From a macro perspective, the biodegradation process can be broken down into three stages. In the first stage, a particular enzyme secreted by microorganisms can lead to the depolymerization of polyethylene molecular chains. In the second stage, the microorganisms absorb the products of the first stage and transform them into the energy they need. In the third stage, the microorganisms use these products to finish their own cellular metabolism and convert them into other compounds [47].

In conclusion, the degradation of polymers under actual conditions is frequently a combination of various degradation mechanisms because the mechanism of degradation of polymers is quite complex and no one mechanism can fully describe the situation. For our investigation into the service life of polyethylene materials, it is crucial to comprehend the biotic and abiotic causes of degradation.

3. General Service Life of Polyethylene

Due to their strength, durability, and low cost when compared to other materials, polyethylene-based products are frequently seen in daily life. This low cost significantly lowers manufacturing costs and promotes the sustainable growth of the global economy.

Polyethylene materials are commonly used for the packaging of food products. The materials used to create food packaging are produced in a way that does not detract from the food’s flavor, appearance, or nutritional value. In order to ensure that the shelf life of the packaging material is longer than the shelf life of the food itself, it is crucial to safeguard the food’s quality. This is because the substances in the packaging material may spread into the food and harm it.

High-density polyethylene, which is frequently used for cable sheathing and has an initial design life of roughly 50 years, typically does not last as long as predicted outdoors due to numerous uncontrollable circumstances. Due to prolonged exposure to UV light, the cable sheath typically cracks after fewer than 10 years of operation in terms of ultraviolet light alone [70].

Natural gas and drinking water are both transported via polyethylene pipes because of their flexibility, light weight, ease of connecting between pipes, and comparatively low installation costs [71]. The polyethylene material will deteriorate and age with continued use, which will affect the pipe’s functionality. Premature pipe damage can result in major safety issues, such as gas leaks, which can seriously endanger people’s lives and property. Premature pipe damage also causes inconveniences in our daily lives. The DuPont Company has been employing polyethylene pipes to transmit natural gas on a massive scale for about 57 years [72], but the lifespan of the pipeline cannot be ignored due to the rising safety issues.

Notable medical uses for polyethylene include complete hip replacements. One of the best therapies for advanced femoral head necrosis is total hip replacement, which typically has a lifespan of at least ten years [20]. Traditional polyethylene has been replaced with highly cross-linked polyethylene since it is extremely prone to wear and tear during use [73].

Materials made of polyethylene are frequently employed in horticulture and agriculture. Films are the primary form of application in agriculture [65], and they are typically used as mulch to cover crops [74]. By more effectively blocking all types of weather that are not favorable for crop growth, such as violent storms, polyethylene mulch can reduce the growth of weeds, retain the moisture and nutrients needed by crops [66], and provide a desirable growing environment for crops. In order to prevent soil contamination, polyethylene mulch is recycled after use and normally lasts a few months to a year outdoors [75]. If polyethylene film breaks down while in use, the ensuing degradation chemicals may be environmentally hazardous. They may also seep into rivers and contaminate the water [76]. To prevent unwanted environmental pollution, it is crucial to recycle polyethylene film within a set time range.

Polyethylene has many other applications that we will not discuss here, but in summary, it is critical to precisely estimate the material's performance to precisely predict the material's life during its service life.

4. General Service Life of Polyethylene

Understanding the degradation process is crucial for polyethylene applications. To gauge the degree of performance degradation of the product, or, in other words, to further gauge the robustness of polyethylene products in long-term use situations, it is important to first comprehend how long the process of degradation takes to become obvious [47]. As a result, when carrying out pertinent experimental tests, the material's aging must be sped up [77]. Accelerated aging techniques are useful for estimating the remaining useful life of polymeric materials like polyethylene, and they can be contrasted to choose the most appropriate technique [78–83].

According to a widely used standard protocol for accelerated aging tests, polyethylene materials are put through cyclic tests in one or more substances for a specified amount of time or a specified number of cycles. To alter the effect of the same substance, the content of the substance utilized as a variable in this test procedure should be significantly different from the level of the substance itself during usage [84–86]. Depending on the needs of the experiment, these studies are typically carried out in suitable climate chambers where polyethylene samples may be exposed to high temperatures or humidity [87,88], UV radiation [89,90], various acids, bases, salts, etc. [91]. The parameters, which are dependent on the particular test conditions, must be decided upon as the initial stage in constructing an accelerated aging technique [92]. The ability to manage whether environmental elements are increasing or decreasing has a significant impact on the test's dependability [93]. In a perfect scenario, the environmental elements that the experiment simulates would be as similar to those in the natural state as possible, and the experiment's duration would be kept to a minimum. The level of testing that is being conducted now, however, is still far below what is optimal for experiments.

5. Prediction Techniques for Polyethylene Materials

5.1. Thermogravimetric Analysis for Kinetic Modeling

In recent decades, predicting the lifetime of polymeric materials such as polyethylene has become a significant research issue [94–96]. The mass decomposition of materials that are linearly dependent on time and temperature can be determined using thermogravimetric analysis (TGA) [97], which is frequently used to research the mass decomposition and kinetics of polyethylene materials. It is challenging to study each stage of the polyethylene breakdown process separately using a straightforward kinetic model because of how complex it is [98,99]. Approaches based on single-step approximations, either model-free or model-fitting methods, are typically employed to explain polyethylene dynamics [100].

The degree of conversion that changes with time or temperature is referred to as the reaction rate in thermogravimetric analysis research, and the conversion rate α is determined using Equation (12) in terms of mass loss.

$$\alpha = \frac{\omega_0 - \omega_t}{\omega_0 - \omega_\infty} = \frac{\Delta\omega}{\Delta\omega_0} \quad (12)$$

where ω_0 , ω_t , and ω_∞ stand for the initial mass, the mass at temperature t , and the final mass, which is the mass at which the mass loss is practically constant, respectively. The product of two functions, one of which is dependent on temperature T and the other on the rate of the reaction, is typically used to indicate the conversion rate of a kinetic process. The general kinetic model of degradation is defined by Equation (13) [101]:

$$\frac{d\alpha}{dt} = K(T)f(\alpha) \tag{13}$$

where $f(\alpha)$ is the transformation function, and $K(T)$ is the temperature-dependent function given by the Arrhenius Equation (14) [102].

$$K(T) = Ae^{-E_a/RT} \tag{14}$$

Thus, Equation (13) can be further written as:

$$\frac{d\alpha}{dt} = Aexp\left(-\frac{E_a}{RT}\right)f(\alpha) \tag{15}$$

where A is the pre-exponential factor, E_a is the activation energy, and R is the gas constant. The reaction model has various forms, some of which are shown in Table 2.

Table 2. Kinetic model and its conversion function [100].

Kinetic Model	Symbol	f(α)
n-order reactions		
First order	F_1	$1 - \alpha$
Second order	F_2	$(1 - \alpha)^2$
n^{th} order	F_n	$(1 - \alpha)^n$
Diffusion		
1-D diffusion	D_1	$1/2\alpha$
2-D diffusion	D_2	$[-\ln(1 - \alpha)]^{-1}$
3-D diffusion–Jander	D_3	$3/2(1 - \alpha)^{\frac{2}{3}} [1 - (1 - \alpha)^{\frac{1}{3}}]^{-1}$
3-D diffusion–Ginstling–Brounshtein	D_4	$3/2 [(1 - \alpha)^{-\frac{1}{3}} - 1]^{-1}$
Phase-boundary reactions		
Contracting area	R_2	$2(1 - \alpha)^{\frac{1}{2}}$
Contracting volume	R_3	$3(1 - \alpha)^{\frac{2}{3}}$
Prout–Tompkins	B_1	$\alpha(1 - \alpha)$
expanded Prout–Tompkins	B_n	$(1 - \alpha)^n \alpha^m$
First order with autocatalysis	C_1	$(1 - \alpha)^{(1+KcatX)}$
n^{th} order with autocatalysis	C_n	$(1 - \alpha)^{n(1+KcatX)}$
Nucleation and nuclei growth		
Avrami–Erofeev	A_2	$2(1 - \alpha) [-\ln(1 - \alpha)]^{\frac{1}{2}}$
Avrami–Erofeev	A_3	$3(1 - \alpha) [-\ln(1 - \alpha)]^{\frac{2}{3}}$
Avrami–Erofeev	A_n	$n(1 - \alpha) [-\ln(1 - \alpha)]^{\frac{n-1}{n}}$

5.2. Arrhenius Equation

5.2.1. General Arrhenius Equation

Accelerated aging experiments offer a reliable foundation for estimating the life of polyethylene materials. Temperature influences the time to failure or aging efficiency of polyethylene materials, and both factors are important for more accurately estimating the performance of polyethylene materials. The Arrhenius connection is the foundation of the most significant method for polyethylene aging. Svante Arrhenius, a Swedish chemist,

presented the Arrhenius equation (Equation (14)) in 1889. It is an empirical chemical kinetic equation that describes the rate of reaction as a function of temperature [103]. The dependence of the kinetics of some simple chemicals' chemical reactions on the critical element of temperature is extremely well described by the Arrhenius equation. The material produces a very modest reaction rate at very low temperatures, according to the Arrhenius equation, yet the minimum value will not be zero. The following conditions must be met to use the Arrhenius equation: (1) There must be only one main chemical reaction that causes thermal deterioration within a specific temperature range, and this significant chemical reaction should serve as the test's starting point [104–107]. (2) First-order or other fixed-order kinetics govern the process of degradation [105,108]. (3) The degradation does not appreciably alter at time zero. (4) There has been no phase change [106,107]. (5) The experimental study's temperature range was somewhat constrained to prevent the accuracy of the test results from being impacted by further degradation mechanisms [109]. (6) Throughout the test's deterioration range, the activation energy should remain constant [110]. The non-exponential form of Equation (16) can be used to represent the Arrhenius equation, making it simpler to use and allowing for graphical interpretation [111]:

$$\ln K(T) = \ln A - \frac{E_a}{RT} \tag{16}$$

However, it is not accurate enough to detect the aging process of the material with a single experiment, so it is necessary to learn more about the change curve of material properties versus time under several experimental conditions, as shown in Figure 3, and use it as a foundation for material life speculation.

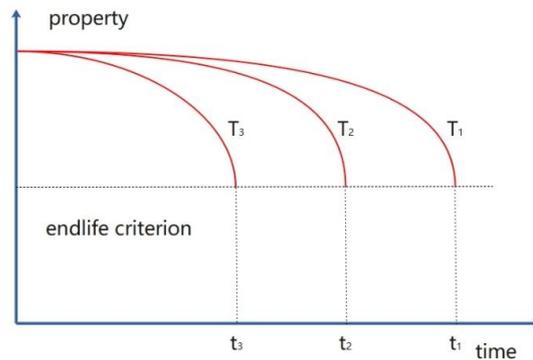


Figure 3. Variation in material characteristics as a function of temperature and time [112].

By plotting the relationship between $\ln K(T)$ and $1/T$ in the equation's linear relationship, the least squares method can be used to best fit the data. It is possible to calculate for E_a and A the slope and intercept of the fitted line as shown in Figure 4.

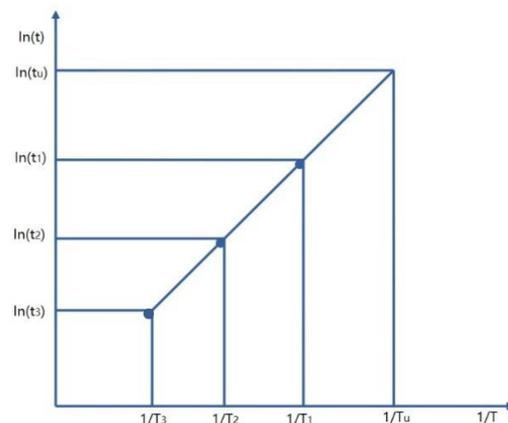


Figure 4. Variation in material characteristics [112].

5.2.2. The modified Arrhenius Equation

The Arrhenius equation has undergone several revisions, and the updated equation now accounts for the impact of relative humidity on the rate of degradation (Equation (17)) [105,106,113–115]:

$$\ln K(T) = \ln A - \frac{E_a}{RT} + B(\%RH) \quad (17)$$

where $\ln K(T)$ is affected linearly by the humidity sensitivity component B at a constant temperature. In the examined range, it is presumed that the relative humidity has an impact only on the molecular mobility and not on the reaction route [106,114]. The frequency of molecule collisions determines the degree and extent of a substance's migration within a material, which is known as molecular mobility [106]. Equation (18) can be used to get B from the intercept of the line to B at constant temperature, where $\ln a - E_a/RT$ is a constant term. Equation (18) can also be used to calculate B from the slope of $\ln K(T)$ to $\%RH$:

$$\ln K(T) = \text{intercept} + B(\%RH) \quad (18)$$

Numerous investigations have conclusively demonstrated that some degradation processes can be adequately characterized by straightforward linear Arrhenius equations [116–119]. As Arrhenius is dependable, time-efficient, and makes it simple to compute changes in aging performance, it is the approach of choice for life prediction in the majority of studies. On the basis of these examples, it can be demonstrated that the Arrhenius equation may be used to forecast the life of polymeric materials other than polyethylene.

5.3. Equal Conversion Rate Method

One of the more trustworthy kinetic approaches for working with thermal analysis data is the equal conversion rate method [120,121]. The main benefit of isoconversion methods, which are based on the isoconversion principle, is that they do not necessitate the assumption of any kind of reaction model $f(\alpha)$ in order to calculate the effective activation energy E_a . Thermal analysis techniques can also be used to measure changes in the overall reaction rate. Analyzing the change in E_a reveals the change in the response mechanism. This method is known as E_a -dependence [122].

To create a more accurate activation energy E_a as a function of the degree of conversion α , the equal conversion rate technique calls for trials at various temperatures. As a result of the significant variation of E_a with α , which suggests that the process is kinetically complex, the E_a -dependence was evaluated using the isotransformation rate method and used as a foundation for kinetic analysis in order to comprehend the intricate nature of the experiment's process and produce accurate kinetic predictions [123].

5.3.1. Ozawa–Flynn–Wall (OFW) Method

Based on the mass loss and temperature data of the polyethylene material at various heating rates, the Ozawa–Flynn–Wall (OFW) approach calculates the activation energy E_a of the thermal degradation process [124]. The complexity of the decomposition mechanism can be ascertained using this method, which does not necessitate prior knowledge of the steps of the degradation mechanism used by the material. Instead, the activation energy for various conversion rates can be assessed. The conversion rate α and the reaction model $g(\alpha)$, which are integrated based on the Doyle approximation, are considered constants in this method despite variations in the heating rate [125] as shown in Equation (19) [126,127]:

$$\ln \beta = \ln \frac{AE_a}{Rg(\alpha)} - 5.331 - 1.052 \frac{E_a}{RT_p} \quad (19)$$

where β is the heating rate, E_a is the activation energy, R is the gas constant, and T_p is the peak temperature. The experimental thermal spectra captured at the heating rate can be used to derive a linear regression of $\ln \beta = f(1/T)$, and the slope of the straight line can be used to calculate the activation energy E_a at a constant conversion rate α [126].

The Ozawa–Flynn–Wall (OFW) method can be used in reaction systems where the activation energy changes over time; however, it may not work when various reaction types with various activation energies coexist. Additionally, competitive responses involving a range of different products cannot be studied using the Ozawa–Flynn–Wall (OFW) Method [128].

5.3.2. Friedman Method

The integral and differential approaches make up the equal conversion rate method [120,129]. In the differential approach, one of the simplest ways to determine the activation energy is by the Friedman method [130] as shown in Equation (20):

$$\ln \frac{d\alpha}{dt} = \ln A + \ln f(\alpha) - \frac{E_a}{RT} \quad (20)$$

Equation (20) can be further expressed as follows when several runs with various constant heating rates are taken into account and given values for [131]:

$$\ln \beta \frac{d\alpha}{dt} = \ln A + \ln f(\alpha) - \frac{E_a}{RT} \quad (21)$$

According to the experimental thermal spectrum captured at the heating rate, the graph of $\ln(\beta d\alpha/dt)$ vs. $1/T$ should be a straight line for the conversion $\alpha = \text{constant}$ [100]. α is constant when $\ln A + \ln f(\alpha)$ is constant, despite the fact that the heating rate β is varied [132]. By taking fixed readings of the conversion rate α , temperature T , and reaction rate $d\alpha/dt$, the activation energy E_a may be estimated from the slope denoted by $\ln(d\alpha/dt)$ for tests carried out at various heating rates [131].

The Friedman approach is more precise than the integral method while not using mathematical approximations such as other integration methods. However, given the potential variability of the reaction rate, the Friedman approach necessitates a high base of thermal analysis equipment [120,133]. Any test, including dynamic and isothermal tests, can be subjected to the Friedman model. Due to experimental flaws or the inherent uncertainty of the differential approach, this method's sensitivity to noise makes it potentially less reliable for kinetic data acquired by thermogravimetric analysis (TGA) [131].

5.3.3. Coats–Redfern Method

The Coats–Redfern method is an integral approach based on an equation and connected to the thermal deterioration mechanism (22) [134]:

$$\ln \left[\frac{g(\alpha)}{T^2} \right] = \ln \left(\frac{AR}{\beta E_a} \right) - \frac{E_a}{RT} \quad (22)$$

where the finger front factor A can be calculated from the intercept of the straight line, the activation energy E_a can be calculated from the slope of the line drawn between $\ln [g(\alpha)/T^2]$ and $1/T$, and $g(\alpha)$ can vary depending on the model and mechanism of the reaction.

5.3.4. Kissinger Method and Kissinger–Akahira–Sunose (KAS) Method

The original Kissinger method was proposed in 1957, and Kissinger made the premise that the experimental conditions barely affect the reaction rate and that it reaches a maximum at a temperature T_p that corresponds to a specific conversion rate α . In this instance, only non-isothermal conditions are suitable for determining the manifest activation energy E_a of the crystallization process, which is proportional to the slope of the maximum value corresponding to the crystal temperature. The heating rate β often affects the conversion rate α . The Kissinger equation is shown in Equation (23) [135]:

$$\ln \left(\frac{\beta}{T_p^2} \right) = \ln \left(\frac{AR}{E_a} \right) - \frac{E_a}{RT_p} \quad (23)$$

where T_p is the peak temperature, and the activation energy E_a can be obtained from the slope of the line $\ln(\beta/T_p^2)$ to $1/T_p$.

According to the Kissinger–Akahira–Sunose (KAS) technique, the activation energy is assumed to be constant for a specific conversion rate [136,137]. The method is based on Equation (24) [138,139]:

$$\ln\left(\frac{\beta}{T_p^2}\right) = \ln\left(\frac{AR}{E_a f(\alpha)}\right) - \frac{E_a}{RT_p} \quad (24)$$

where the $\ln(\beta/T_p^2)$ versus $1/T_p$ curve is a straight line, and the slope and intercept can be used to calculate the activation energy E_a and the value of pre-exponential factor A for a given type.

The Kissinger–Akahira–Sunose (KAS) method corrects some biases in the Ozawa–Flynn–Wall (OFW) method by using the Coats–Redfern approximation, and the Kissinger–Akahira–Sunose (KAS) method provides a more accurate estimate of the activation energy [133,134].

5.3.5. Augis and Bennett's Method

The Kissinger method began by not specifying the number of reaction levels, thereby determining the activation energy of the n -level reaction. Regardless of the fitted kinetic model, the method allows for the determination of the reaction's activation energy without knowledge of the reaction mechanism [140]. Augis and Bennett proposed the following equation as a complement to the Kissinger method, based on non-isothermal differential thermal analysis (DTA) and differential scanning calorimetry (DSC):

$$\ln\left(\frac{\beta}{T_p - T_0}\right) = \ln A - \frac{E_a}{RT_p} \quad (25)$$

where β is the heating rate, E_a is the activation energy, R is the gas constant, T_p is the temperature corresponding to the peak of the differential scanning calorimetry (DSC) or differential thermal analysis (DTA) curve, and T_0 is the starting temperature.

The accuracy of the DTA or DSC curve plotting and the heating rate β influence the evaluation of Augis and Bennett's method for the onset temperature T_0 . Augis and Bennett recommend using a single T_0 value for all heating rates, i.e., one that is lower than the lowest starting temperature corresponding to the lowest heating rate [141].

5.3.6. Advanced Isoconversional Methods

The differential method has the advantage of not requiring approximations and can be applied to isothermal, non-isothermal, or more complex temperature tests of any type. The main disadvantage of the differential method is the possibility of experimental result value instability [142]. To address some of the shortcomings of the commonly used integration method, some researchers pioneered the advanced equal conversion method [120,143,144]. The Vyazovkin method, which is one of the more sophisticated isotransformation techniques, is represented by Equations (26) and (27):

$$\Phi(E_\alpha) = \sum_{i=1}^n \sum_{j \neq i}^n \frac{J[E_\alpha, T_i(t_\alpha)]}{J[E_\alpha, T_j(t_\alpha)]} \quad (26)$$

$$J[E_\alpha, T(t_\alpha)] = \int_{t_\alpha - \Delta\alpha}^{t_\alpha} \exp\left[\frac{-E_\alpha}{RT(t)}\right] dt \quad (27)$$

where E_α is the effective activation energy and the value of E_α is the value that minimizes the function $\Phi(E_\alpha)$. This nonlinear kinetic approach (NLN) deals with a set of n experiments performed at different temperatures $T_i(t)$, which can be numerically integrated over time using the trapezoidal method. Exact interpolation using the Lagrangian algorithm determines the time $t_{\alpha,i}$ and temperature $T_{\alpha,i}$ associated with the selected value of α for each i th temperature program [145].

6. Conclusions

In modern society, polyethylene materials are utilized in a variety of applications, but as their use increases, their initial performance qualities tend to change. Temperature, light, pressure, chemical attack, mechanical stress, microorganisms, and other factors can all affect the degradation of polyethylene materials. This influence is frequently synergistic, making polyethylene degradation extremely complex. Many researchers have developed various kinetic methods for predicting the lifetime of polyethylene materials, and this paper describes the most common and widely used kinetic methods.

The isoconversion method derives from the Ozawa–Flynn–Wall (OFW) method and the Friedman method, both of which do not require a mathematical model and instead use several curves at different heating rates to calculate the kinetic parameters at the same conversion rate and obtain the activation energy. The multi-curve method is another name for the equal conversion rate method. With the introduction of the Kissinger–Akahira–Sunose (KAS) method, the accuracy of the equal conversion rate method has improved. Kissinger and OFW are model-free analyses, which means that the activation energy is calculated without taking into account the kinetic model of the reaction process. Friedman's method has the advantage of not being limited to linear changes in heating rate and exhibiting simplicity, adequacy, and accuracy. The advanced isotransformation rate method is now widely acknowledged as one of the most precise methods for estimating activation energies from TGA experiments.

Due to the numerous applications of polyethylene materials in people's lives, the extensive use of polyethylene materials can lead to environmental pollution. Extending the service life of polyethylene can promote the development of the 5Rs [146] for reducing environmental pollution, therefore, the life prediction of polyethylene and other polymeric materials is critical.

Author Contributions: Conceptualization, Y.W.; Writing—original draft, G.F.; Funding acquisition, Y.W.; Investigation, Y.W. and D.Y.; Resources, Y.W. and N.L.; Supervision, Y.W. and H.L.; Validation, Q.L.; Writing—review and editing, J.T. and G.F. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Natural Science Foundation of Xinjiang Uygur Autonomous Region (no. 2022D01C389), the Xinjiang University Doctoral Start-up Foundation (no. 620321029), and the Science and Technology Planning Project of State Administration for Market Regulation (no. 2022MK201).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data are not publicly available.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Dehbi, A.; Mourad, A.-H.I.; Bouaza, A. Ageing effect on the properties of tri-layer polyethylene film used as greenhouse roof. *Procedia Eng.* **2011**, *10*, 466–471. [[CrossRef](#)]
2. Fouad, H.; Mourad, A.-H.; Barton, D. Effect of pre-heat treatment on the static and dynamic thermo-mechanical properties of ultra-high molecular weight polyethylene. *Polym. Test.* **2005**, *24*, 549–556. [[CrossRef](#)]
3. Mohamed, F.H.; Mourad, A.-H.I.; Barton, D.C. UV irradiation and aging effects on nanoscale mechanical properties of ultra high molecular weight polyethylene for biomedical implants. *Plast. Rubber Compos.* **2008**, *37*, 346–352. [[CrossRef](#)]
4. Tiffour, I.; Dehbi, A.; Mourad, A.-H.I.; Belfedal, A. Synthesis and characterization of a new organic semiconductor material. *Mater. Chem. Phys.* **2016**, *178*, 49–56. [[CrossRef](#)]
5. Mourad, A.-H.I.; Elsayed, H.F.; Barton, D.C.; Kenawy, M.; Abdel-Latif, L.A. Ultra high molecular weight polyethylene deformation and fracture behaviour as a function of high strain rate and triaxial state of stress. *Int. J. Fract.* **2003**, *120*, 501–515. [[CrossRef](#)]
6. Mourad, A.-H.I.; Mozumder, M.S.; Mairpady, A.; Pervez, H.; Kannuri, U.M. Optimization of injection molding parameters for HDPE/TiO₂ nanocomposites fabrication with multiple performance characteristics using the Taguchi method and grey relational analysis. *Materials* **2016**, *9*, 710. [[CrossRef](#)]

7. Paxton, N.C.; Allenby, M.C.; Lewis, P.M.; Woodruff, M.A. Biomedical applications of polyethylene. *Eur. Polym. J.* **2019**, *118*, 412–428. [[CrossRef](#)]
8. Mozumder, M.S.; Mourad, A.-H.I.; Mairpady, A.; Pervez, H.; Haque, E. Effect of TiO₂ nanofiller concentration on the mechanical, thermal and biological properties of HDPE/TiO₂ nanocomposites. *J. Mater. Eng. Perform.* **2018**, *27*, 2166–2181. [[CrossRef](#)]
9. Weon, J.-I. Effects of thermal ageing on mechanical and thermal behaviors of linear low density polyethylene pipe. *Polym. Degrad. Stab.* **2010**, *95*, 14–20. [[CrossRef](#)]
10. Holder, S.L.; Hedenqvist, M.S.; Nilsson, F. Understanding and modelling the diffusion process of low molecular weight substances in polyethylene pipes. *Water Res.* **2019**, *157*, 301–309. [[CrossRef](#)]
11. Zanasi, T.; Fabbri, E.; Pilati, F. Qualification of pipe-grade HDPEs: Part I, development of a suitable accelerated ageing method. *Polym. Test.* **2009**, *28*, 96–102. [[CrossRef](#)]
12. Contino, M.; Andena, L.; Rink, M.; Marra, G.; Resta, S. Time-temperature equivalence in environmental stress cracking of high-density polyethylene. *Eng. Fract. Mech.* **2018**, *203*, 32–43. [[CrossRef](#)]
13. Gong, Y.; Wang, S.-H.; Zhang, Z.-Y.; Yang, X.-L.; Yang, Z.-G.; Yang, H.-G. Degradation of sunlight exposure on the high-density polyethylene (HDPE) pipes for transportation of natural gases. *Polym. Degrad. Stab.* **2021**, *194*, 109752. [[CrossRef](#)]
14. Frank, A.; Pinter, G. Evaluation of the applicability of the cracked round bar test as standardized PE-pipe ranking tool. *Polym. Test.* **2014**, *33*, 161–171. [[CrossRef](#)]
15. Yeh, C.-L.; Nikolić, M.A.; Gomes, B.; Gauthier, E.; Laycock, B.; Halley, P.; Bottle, S.E.; Colwell, J.M. The effect of common agrichemicals on the environmental stability of polyethylene films. *Polym. Degrad. Stab.* **2015**, *120*, 53–60. [[CrossRef](#)]
16. Setnickova, K.; Petrychkovych, R.; Reznickova, J.; Uchytíl, P. A novel simple and efficient procedure for the pervaporation transport study of binary mixtures through polymeric membranes: Tested systems propanol isomers—Water—polyethylene membrane. *J. Taiwan Inst. Chem. Eng.* **2016**, *58*, 49–56. [[CrossRef](#)]
17. Kircheva, N.; Outin, J.; Perrier, G.; Ramousse, J.; Merlin, G.; Lyautey, E. Bio-electrochemical characterization of air-cathode microbial fuel cells with microporous polyethylene/silica membrane as separator. *Bioelectrochemistry* **2015**, *106*, 115–124. [[CrossRef](#)]
18. Kindsfater, K.A.; Pomeroy, D.; Clark, C.; Gruen, T.A.; Murphy, J.; Himden, S. In vivo performance of moderately crosslinked, thermally treated polyethylene in a prospective randomized controlled primary total knee arthroplasty trial. *J. Arthroplast.* **2015**, *30*, 1333–1338. [[CrossRef](#)]
19. So, K.; Goto, K.; Kuroda, Y.; Matsuda, S. Minimum 10-year wear analysis of highly cross-linked polyethylene in cementless total hip arthroplasty. *J. Arthroplast.* **2015**, *30*, 2224–2226. [[CrossRef](#)]
20. Min, B.-W.; Cho, C.-H.; Son, E.-S.; Lee, K.-J.; Lee, S.-W.; Song, K.-S. Highly cross-linked polyethylene in total hip arthroplasty in patients younger than 50 years with osteonecrosis of the femoral head: A minimum of 10 years of follow-up. *J. Arthroplast.* **2020**, *35*, 805–810. [[CrossRef](#)]
21. Azeko, S.T.; Mustapha, K.; Annan, E.; Odusanya, O.S.; Soboyejo, W.O. Recycling of polyethylene into strong and tough earth-based composite building materials. *J. Mater. Civ. Eng.* **2016**, *28*, 04015104. [[CrossRef](#)]
22. Azeko, S.T.; Arthur, E.K.; Danyuo, Y.; Babagana, M. Mechanical and physical properties of laterite bricks reinforced with reprocessed polyethylene waste for building applications. *J. Mater. Civ. Eng.* **2018**, *30*, 04018039. [[CrossRef](#)]
23. Tajeddin, B.; Arabkhedri, M. Polymers and food packaging. In *Polymer Science and Innovative Applications*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 525–543. [[CrossRef](#)]
24. Kahlen, S.; Jerabek, M.; Wallner, G.; Lang, R. Characterization of physical and chemical aging of polymeric solar materials by mechanical testing. *Polym. Test.* **2010**, *29*, 72–81. [[CrossRef](#)]
25. Pleșa, I.; Noțingher, P.V.; Stancu, C.; Wiesbrock, F.; Schlögl, S. Polyethylene nanocomposites for power cable insulations. *Polymers* **2018**, *11*, 24. [[CrossRef](#)] [[PubMed](#)]
26. Wang, T.; Ma, Y.; Ji, R. Aging processes of polyethylene mulch films and preparation of microplastics with environmental characteristics. *Bull. Environ. Contam. Toxicol.* **2021**, *107*, 736–740. [[CrossRef](#)] [[PubMed](#)]
27. Leja, K.; Lewandowicz, G. Polymer biodegradation and biodegradable polymers—A review. *Pol. J. Environ. Stud.* **2010**, *19*, 255–266.
28. Kasirajan, S.; Ngouajio, M. Polyethylene and biodegradable mulches for agricultural applications: A review. *Agron. Sustain. Dev.* **2012**, *32*, 501–529. [[CrossRef](#)]
29. Vázquez-Morillas, A.; Beltrán-Villavicencio, M.; Alvarez-Zeferino, J.C.; Osada-Velázquez, M.H.; Moreno, A.; Martínez, L.; Yáñez, J.M. Biodegradation and ecotoxicity of polyethylene films containing pro-oxidant additive. *J. Polym. Environ.* **2016**, *24*, 221–229. [[CrossRef](#)]
30. Ammala, A.; Bateman, S.; Dean, K.; Petinakis, E.; Sangwan, P.; Wong, S.; Yuan, Q.; Yu, L.; Patrick, C.; Leong, K. An overview of degradable and biodegradable polyolefins. *Prog. Polym. Sci.* **2011**, *36*, 1015–1049. [[CrossRef](#)]
31. Struik, L.C.E. The mechanical and physical ageing of semicrystalline polymers: 1. *Polymer* **1987**, *28*, 1521–1533. [[CrossRef](#)]
32. Castagnet, S.; Thilly, L. High-pressure dependence of structural evolution in polyamide 11 during annealing. *J. Polym. Sci. Part B Polym. Phys.* **2009**, *47*, 2015–2025. [[CrossRef](#)]
33. Gill, T.; Knapp, R.; Bradley, S.; Bradley, W. Long term durability of crosslinked polyethylene tubing used in chlorinated hot water systems. *Plast. Rubber Compos.* **1999**, *28*, 309–313. [[CrossRef](#)]
34. Chandran, K.R. Mechanical fatigue of polymers: A new approach to characterize the SN behavior on the basis of macroscopic crack growth mechanism. *Polymer* **2016**, *91*, 222–238. [[CrossRef](#)]

35. Rueda, F.; Torres, J.; Machado, M.; Frontini, P.; Otegui, J. External pressure induced buckling collapse of high density polyethylene (HDPE) liners: FEM modeling and predictions. *Thin-Walled Struct.* **2015**, *96*, 56–63. [[CrossRef](#)]
36. Gorghiu, L.; Jipa, S.; Zaharescu, T.; Setnescu, R.; Mihalcea, I. The effect of metals on thermal degradation of polyethylenes. *Polym. Degrad. Stab.* **2004**, *84*, 7–11. [[CrossRef](#)]
37. Desai, V.; Shenoy, M.; Gogate, P. Ultrasonic degradation of low-density polyethylene. *Chem. Eng. Process. Process Intensif.* **2008**, *47*, 1451–1455. [[CrossRef](#)]
38. Mierzwa-Hersztek, M.; Gondek, K.; Kopeć, M. Degradation of polyethylene and biocomponent-derived polymer materials: An overview. *J. Polym. Environ.* **2019**, *27*, 600–611. [[CrossRef](#)]
39. La Mantia, F.P.; Morreale, M.; Botta, L.; Mistretta, M.C.; Ceraulo, M.; Scaffaro, R. Degradation of polymer blends: A brief review. *Polym. Degrad. Stab.* **2017**, *145*, 79–92. [[CrossRef](#)]
40. Rolón-Garrido, V.H.; Kruse, M.; Wagner, M.H. Size exclusion chromatography of photo-oxidated LDPE by triple detection and its relation to rheological behavior. *Polym. Degrad. Stab.* **2015**, *111*, 46–54. [[CrossRef](#)]
41. Osawa, Z.; Kurisu, N.; Nagashima, K.; Nakano, K. The effect of transition metal stearates on the photodegradation of polyethylene. *J. Appl. Polym. Sci.* **1979**, *23*, 3583–3590. [[CrossRef](#)]
42. Gugumus, F. Effect of temperature on the lifetime of stabilized and unstabilized PP films. *Polym. Degrad. Stab.* **1999**, *63*, 41–52. [[CrossRef](#)]
43. Hakkarainen, M.; Albertsson, A.-C. Environmental degradation of polyethylene. *Long Term Prop. Polyolefins* **2004**, 177–200. [[CrossRef](#)]
44. Saiz-Jimenez, C. Biodeterioration vs biodegradation: The role of microorganisms in the removal of pollutants deposited on historic buildings. *Int. Biodeterior. Biodegrad.* **1997**, *40*, 225–232. [[CrossRef](#)]
45. Lucas, N.; Bienaime, C.; Belloy, C.; Queneudec, M.; Silvestre, F.; Nava-Saucedo, J.-E. Polymer biodegradation: Mechanisms and estimation techniques—A review. *Chemosphere* **2008**, *73*, 429–442. [[CrossRef](#)]
46. Wilkes, R.; Aristilde, L. Degradation and metabolism of synthetic plastics and associated products by *Pseudomonas* sp.: Capabilities and challenges. *J. Appl. Microbiol.-Gy* **2017**, *123*, 582–593. [[CrossRef](#)]
47. Emadian, S.M.; Onay, T.T.; Demirel, B. Biodegradation of bioplastics in natural environments. *Waste Manag.* **2017**, *59*, 526–536. [[CrossRef](#)]
48. Restrepo-Flórez, J.-M.; Bassi, A.; Thompson, M.R. Microbial degradation and deterioration of polyethylene—A review. *Int. Biodeterior. Biodegrad.* **2014**, *88*, 83–90. [[CrossRef](#)]
49. Rizzarelli, P.; Rapisarda, M.; Ascione, L.; Degli Innocenti, F.; La Mantia, F.P. Influence of photo-oxidation on the performance and soil degradation of oxo- and biodegradable polymer-based items for agricultural applications. *Polym. Degrad. Stab.* **2021**, *188*, 109578. [[CrossRef](#)]
50. Gardette, M.; Perthue, A.; Gardette, J.; Janecska, T.; Földes, E.; Pukánszky, B.; Therias, S. Photo- and thermal-oxidation of polyethylene: Comparison of mechanisms and influence of unsaturation content. *Polym. Degrad. Stab.* **2013**, *98*, 2383–2390. [[CrossRef](#)]
51. Anju, S.; Prajitha, N.; Sukanya, V.; Mohanan, P. Complicity of degradable polymers in health-care applications. *Mater. Today Chem.* **2020**, *16*, 100236. [[CrossRef](#)]
52. Carrasco, F.; Pagès, P.; Pascual, S.; Colom, X. Artificial aging of high-density polyethylene by ultraviolet irradiation. *Eur. Polym. J.* **2001**, *37*, 1457–1464. [[CrossRef](#)]
53. Pages, P.; Carrasco, F.; Surina, J.; Colom, X. FTIR and DSC study of HDPE structural changes and mechanical properties variation when exposed to weathering aging during Canadian winter. *J. Appl. Polym. Sci.* **1996**, *60*, 153–159. [[CrossRef](#)]
54. François-Heude, A.; Richaud, E.; Desnoux, E.; Colin, X. A general kinetic model for the photothermal oxidation of polypropylene. *J. Photochem. Photobiol. A Chem.* **2015**, *296*, 48–65. [[CrossRef](#)]
55. Hsu, Y.-C.; Weir, M.P.; Truss, R.W.; Garvey, C.J.; Nicholson, T.M.; Halley, P.J. A fundamental study on photo-oxidative degradation of linear low density polyethylene films at embrittlement. *Polymer* **2012**, *53*, 2385–2393. [[CrossRef](#)]
56. Wiles, D.M.; Scott, G. Polyolefins with controlled environmental degradability. *Polym. Degrad. Stab.* **2006**, *91*, 1581–1592. [[CrossRef](#)]
57. Feldman, D. Polymer weathering: Photo-oxidation. *J. Polym. Environ.* **2002**, *10*, 163–173. [[CrossRef](#)]
58. Carpenter, K.; Janssens, M. Using heat release rate to assess combustibility of building products in the cone calorimeter. *Fire Technol.* **2005**, *41*, 79–92. [[CrossRef](#)]
59. Briassoulis, D. The effects of tensile stress and the agrochemical Vapam on the ageing of low density polyethylene (LDPE) agricultural films. Part I. Mechanical behaviour. *Polym. Degrad. Stab.* **2005**, *88*, 489–503. [[CrossRef](#)]
60. Müller, R.-J.; Witt, U.; Rantze, E.; Deckwer, W.-D. Architecture of biodegradable copolyesters containing aromatic constituents. *Polym. Degrad. Stab.* **1998**, *59*, 203–208. [[CrossRef](#)]
61. Tsuji, H.; Ikada, Y. Properties and morphology of poly (L-lactide) 4. Effects of structural parameters on long-term hydrolysis of poly (L-lactide) in phosphate-buffered solution. *Polym. Degrad. Stab.* **2000**, *67*, 179–189. [[CrossRef](#)]
62. He, Y.; Qian, Z.; Zhang, H.; Liu, X. Alkaline degradation behavior of polyesteramide fibers: Surface erosion. *Colloid Polym. Sci.* **2004**, *282*, 972–978. [[CrossRef](#)]
63. Krushelnitzky, R.; Brachman, R. Antioxidant depletion in high-density polyethylene pipes exposed to synthetic leachate and air. *Geosynth. Int.* **2011**, *18*, 63–73. [[CrossRef](#)]

64. Briassoulis, D. Mechanical design requirements for low tunnel biodegradable and conventional films. *Biosyst. Eng.* **2004**, *87*, 209–223. [[CrossRef](#)]
65. Briassoulis, D. Mechanical behaviour of biodegradable agricultural films under real field conditions. *Polym. Degrad. Stab.* **2006**, *91*, 1256–1272. [[CrossRef](#)]
66. Briassoulis, D. Analysis of the mechanical and degradation performances of optimised agricultural biodegradable films. *Polym. Degrad. Stab.* **2007**, *92*, 1115–1132. [[CrossRef](#)]
67. Król-Morkisz, K.; Pielichowska, K. Thermal decomposition of polymer nanocomposites with functionalized nanoparticles. In *Polymer Composites with Functionalized Nanoparticles*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 405–435. [[CrossRef](#)]
68. Beyler, C.L.; Hirschler, M.M. Thermal decomposition of polymers. *SFPE Handb. Fire Prot. Eng.* **2002**, *2*, 111–131.
69. Plota, A.; Masek, A. Lifetime prediction methods for degradable polymeric materials—A short review. *Materials* **2020**, *13*, 4507. [[CrossRef](#)] [[PubMed](#)]
70. Hu, W.; Liu, W.; Ren, X. The study on aging behaviors and critical stress of cross-linked high-density polyethylene during stress and photo-oxidative aging. *J. Polym. Res.* **2019**, *26*, 114. [[CrossRef](#)]
71. Bachir-Bey, T.; Belhaneche-Bensemra, N. Investigation of Polyethylene Pipeline Behavior after 30 Years of Use in Gas Distribution Network. *J. Mater. Eng. Perform.* **2020**, *29*, 6652–6660. [[CrossRef](#)]
72. Brown, N. Intrinsic lifetime of polyethylene pipelines. *Polym. Eng. Sci.* **2007**, *47*, 477–480. [[CrossRef](#)]
73. Dowd, J.E.; Sychterz, C.J.; Young, A.M.; Engh, C.A. Characterization of long-term femoral-head-penetration rates: Association with and prediction of osteolysis. *JBJS* **2000**, *82*, 1102. [[CrossRef](#)] [[PubMed](#)]
74. Lan, T.; Wang, T.; Cao, F.; Yu, C.; Chu, Q.; Wang, F. A comparative study on the adsorption behavior of pesticides by pristine and aged microplastics from agricultural polyethylene soil films. *Ecotoxicol. Environ. Saf.* **2021**, *209*, 111781. [[CrossRef](#)] [[PubMed](#)]
75. Hou, L.; Xi, J.; Liu, J.; Wang, P.; Xu, T.; Liu, T.; Qu, W.; Lin, Y.B. Biodegradability of polyethylene mulching film by two *Pseudomonas* bacteria and their potential degradation mechanism. *Chemosphere* **2022**, *286*, 131758. [[CrossRef](#)] [[PubMed](#)]
76. Derraik, J.G.B. The pollution of the marine environment by plastic debris: A review. *Mar. Pollut. Bull.* **2002**, *44*, 842–852. [[CrossRef](#)] [[PubMed](#)]
77. Arhant, M.; Le Gall, M.; Le Gac, P.-Y. Fracture test to accelerate the prediction of polymer embrittlement during aging—Case of PET hydrolysis. *Polym. Degrad. Stab.* **2022**, *196*, 109848. [[CrossRef](#)]
78. Goliszek, M.; Podkościelna, B.; Sevastyanova, O.; Fila, K.; Chabros, A.; Pączkowski, P. Investigation of accelerated aging of lignin-containing polymer materials. *Int. J. Biol. Macromol.* **2019**, *123*, 910–922. [[CrossRef](#)] [[PubMed](#)]
79. Hukins, D.; Mahomed, A.; Kukureka, S. Accelerated aging for testing polymeric biomaterials and medical devices. *Med. Eng. Phys.* **2008**, *30*, 1270–1274. [[CrossRef](#)]
80. Schoenbeck, M.A. Durability of chlorosulfonated polyethylene geomembrane seams after accelerated aging tests. *Geotext. Geomembr.* **1990**, *9*, 337–341. [[CrossRef](#)]
81. Huang, J.S.; Lu, R.G.; Shi, Y.X.; Zhao, Y.F.; Fang, X.H.; Liu, G.; Li, Z.J. Changes on structural and electrical properties of retired cross-linked polyethylene (XLPE) cable insulation under electro-thermal aging test. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2019; Volume 354. [[CrossRef](#)]
82. Sebaa, M.; Servens, C.; Pouyet, J. Natural and artificial weathering of low-density polyethylene (LDPE): Calorimetric analysis. *J. Appl. Polym. Sci.* **1993**, *47*, 1897–1903. [[CrossRef](#)]
83. Bauker, V.; Huinink, H.P.; Adan, O.C.; van der Ven, L.G. Natural versus accelerated weathering: Understanding water kinetics in bilayer coatings. *Prog. Org. Coat.* **2013**, *76*, 1197–1202. [[CrossRef](#)]
84. Philip, M.; Al-Azzawi, F. Effects of natural and artificial weathering on the physical properties of recycled poly (ethylene terephthalate). *J. Polym. Environ.* **2018**, *26*, 3139–3148. [[CrossRef](#)]
85. Therias, S.; Rapp, G.; Masson, C.; Gardette, J.-L. Limits of UV-light acceleration on the photooxidation of low-density polyethylene. *Polym. Degrad. Stab.* **2021**, *183*, 109443. [[CrossRef](#)]
86. Geng, P.; Song, J.; Tian, M.; Lei, Z.; Du, Y. Influence of thermal aging on AC leakage current in XLPE insulation. *Aip Adv.* **2018**, *8*, 025115. [[CrossRef](#)]
87. Li, H.; Li, J.; Ma, Y.; Yan, Q.; Ouyang, B. The role of thermo-oxidative aging at different temperatures on the crystal structure of crosslinked polyethylene. *J. Mater. Sci. Mater. Electron.* **2018**, *29*, 3696–3703. [[CrossRef](#)]
88. Hedir, A.; Moudoud, M.; Lamrous, O.; Rondot, S.; Jbara, O.; Dony, P. Ultraviolet radiation aging impact on physicochemical properties of crosslinked polyethylene cable insulation. *J. Appl. Polym. Sci.* **2020**, *137*, 48575. [[CrossRef](#)]
89. Doğan, M. Ultraviolet light accelerates the degradation of polyethylene plastics. *Microsc. Res. Tech.* **2021**, *84*, 2774–2783. [[CrossRef](#)]
90. Bredács, M.; Frank, A.; Bastero, A.; Stolarz, A.; Pinter, G. Accelerated aging of polyethylene pipe grades in aqueous chlorine dioxide at constant concentration. *Polym. Degrad. Stab.* **2018**, *157*, 80–89. [[CrossRef](#)]
91. Bolland, J.L. Kinetics of olefin oxidation. *Q. Rev. Chem. Soc.* **1949**, *3*, 1–21. [[CrossRef](#)]
92. Gandhi, K.; Hein, C.L.; van Heerbeek, R.; Pickett, J.E. Acceleration parameters for polycarbonate under blue LED photo-thermal aging conditions. *Polym. Degrad. Stab.* **2019**, *164*, 69–74. [[CrossRef](#)]
93. Nichols, M.; Boisseau, J.; Pattison, L.; Campbell, D.; Quill, J.; Zhang, J.; Smith, N.; Henderson, K.; Seebergh, J.; Berry, D.; et al. An improved accelerated weathering protocol to anticipate Florida exposure behavior of coatings. *J. Coat. Technol. Res.* **2013**, *10*, 153–173. [[CrossRef](#)]

94. Celina, M.; Gillen, K.; Assink, R. Accelerated aging and lifetime prediction: Review of non-Arrhenius behaviour due to two competing processes. *Polym. Degrad. Stab.* **2005**, *90*, 395–404. [[CrossRef](#)]
95. Celina, M.; Gillen, K.; Assink, R. Lifetime predictions for semi-crystalline cable insulation materials: I. Mechanical properties and oxygen consumption measurements on EPR materials. *Polym. Degrad. Stab.* **2006**, *91*, 2146–2156. [[CrossRef](#)]
96. Lainé, E.; Bouvy, C.; Grandidier, J.-C.; Vaes, G. Methodology of Accelerated Characterization for long-term creep prediction of polymer structures to ensure their service life. *Polym. Test.* **2019**, *79*, 106050. [[CrossRef](#)]
97. Kple, M.; Girods, P.; Fagla, B.; Anjorin, M.; Ziegler-Devin, I.; Rogeaume, Y. Kinetic study of low density polyethylene using thermogravimetric analysis, Part 2: Isothermal study. *Waste Biomass Valorization* **2017**, *8*, 707–719. [[CrossRef](#)]
98. Chrissafis, K.; Efthimiadis, K.G.; Polychroniadis, E.K.; Chadjivasiliou, S.C. *Crystallization Kinetics of Amorphous Fe78-xMoxSi9B13*; Aristotle University of Thessaloniki: Thessaloniki, Greece, 2003; No. IKEEART-2010-364. [[CrossRef](#)]
99. Chrissafis, K.; Kyratsi, T.; Paraskevopoulos, K.M.; Kanatzidis, M.G. Crystal/glass phase change in KSb5S8 studied through thermal analysis techniques. *Chem. Mater.* **2004**, *16*, 1932–1937. [[CrossRef](#)]
100. Chrissafis, K. Kinetics of thermal degradation of polymers. *J. Therm. Anal. Calorim.* **2009**, *95*, 273–283. [[CrossRef](#)]
101. Vyazovkin, S. Computational aspects of kinetic analysis.: Part C. The ICTAC Kinetics Project—The light at the end of the tunnel? *Thermochim. Acta* **2000**, *355*, 155–163. [[CrossRef](#)]
102. Budrugaec, P. Theory and practice in the thermoanalytical kinetics of complex processes: Application for the isothermal and non-isothermal thermal degradation of HDPE. *Thermochim. Acta* **2010**, *500*, 30–37. [[CrossRef](#)]
103. Arrhenius, S. Über die Reaktionsgeschwindigkeit bei der Inversion von Rohrzucker durch Säuren. *Z. Für Phys. Chem.* **1889**, *4*, 226–248. [[CrossRef](#)]
104. Baird, J.A.; Taylor, L.S. Evaluation of amorphous solid dispersion properties using thermal analysis techniques. *Adv. Drug Deliv. Rev.* **2012**, *64*, 396–421. [[CrossRef](#)]
105. Gil-Alegre, M.; Bernabeu, J.; Camacho, M.; Torres-Suarez, A. Statistical evaluation for stability studies under stress storage conditions. *Il Farm.* **2011**, *56*, 877–883. [[CrossRef](#)]
106. Waterman, K.C.; Adami, R.C. Accelerated aging: Prediction of chemical stability of pharmaceuticals. *Int. J. Pharm.* **2005**, *293*, 101–125. [[CrossRef](#)]
107. Waterman, K.C. Understanding and predicting pharmaceutical product shelf-life. In *Handbook of Stability Testing in Pharmaceutical Development*; Springer: New York, NY, USA, 2009; pp. 115–135. [[CrossRef](#)]
108. Peleg, M.; Normand, M.D.; Corradini, M.G. The Arrhenius equation revisited. *Crit. Rev. Food Sci. Nutr.* **2012**, *52*, 830–851. [[CrossRef](#)]
109. Oliva, A.; Fariña, J.; Llabrés, M. An improved methodology for data analysis in accelerated stability studies of peptide drugs: Practical considerations. *Talanta* **2012**, *94*, 158–166. [[CrossRef](#)] [[PubMed](#)]
110. Budrugaec, P. On the evaluation of the thermal lifetime of polymeric materials which exhibit a complex mechanism of thermal degradation consisting of two successive reactions. *Polym. Degrad. Stab.* **2000**, *67*, 271–278. [[CrossRef](#)]
111. Tsuji, T.; Mochizuki, K.; Okada, K.; Hayashi, Y.; Obata, Y.; Takayama, K.; Onuki, Y. Time–temperature superposition principle for the kinetic analysis of destabilization of pharmaceutical emulsions. *Int. J. Pharm.* **2019**, *563*, 406–412. [[CrossRef](#)] [[PubMed](#)]
112. Le Huy, M.; Evrard, G. Methodologies for lifetime predictions of rubber using Arrhenius and WLF models. *Die Angew. Makromol. Chem.* **1998**, *261*, 135–142. [[CrossRef](#)]
113. Waterman, K.C.; Carella, A.J.; Gumkowski, M.J.; Lukulay, P.; Macdonald, B.C.; Roy, M.C.; Shamblin, S.L. Improved protocol and data analysis for accelerated shelf-life estimation of solid dosage forms. *Pharm. Res.* **2007**, *24*, 780–790. [[CrossRef](#)]
114. Waterman, K.C. The application of the accelerated stability assessment program (ASAP) to quality by design (QbD) for drug product stability. *AAPS PharmSciTech* **2011**, *12*, 932–937. [[CrossRef](#)]
115. Li, N.; Taylor, L.S.; Mauer, L.J. Degradation kinetics of catechins in green tea powder: Effects of temperature and relative humidity. *J. Agric. Food Chem.* **2011**, *59*, 6082–6090. [[CrossRef](#)]
116. Wang, Y.; Lan, H.-Q.; Meng, T.; Chen, S.; Zuo, J.-D.; Lin, N. A Lifetime Prediction Method of Pressured Gas Polyethylene Pipes by Thermal-Oxidative Aging Test and Tensile Test. *J. Press. Vessel Technol.* **2018**, *140*, 011404. [[CrossRef](#)]
117. Wise, J.; Gillen, K.; Clough, R. An ultrasensitive technique for testing the Arrhenius extrapolation assumption for thermally aged elastomers. *Polym. Degrad. Stab.* **1995**, *49*, 403–418. [[CrossRef](#)]
118. Madej-Kielbik, L.; Kośła, K.; Zielińska, D.; Chmal-Fudali, E.; Maciejewska, M. Effect of accelerated ageing on the mechanical and structural properties of the material system used in protectors. *Polymers* **2019**, *11*, 1263. [[CrossRef](#)] [[PubMed](#)]
119. Koga, Y.; Arao, Y.; Kubouchi, M. Application of small punch test to lifetime prediction of plasticized polyvinyl chloride wire. *Polym. Degrad. Stab.* **2020**, *171*, 109013. [[CrossRef](#)]
120. Vyazovkin, S.; Burnham, A.K.; Criado, J.M.; Pérez-Maqueda, L.A.; Popescu, C.; Sbirrazzuoli, N. ICTAC Kinetics Committee recommendations for performing kinetic computations on thermal analysis data. *Thermochim. Acta* **2011**, *520*, 1–19. [[CrossRef](#)]
121. Vyazovkin, S.; Burnham, A.K.; Favergeon, L.; Koga, N.; Moukhina, E.; Pérez-Maqueda, L.A.; Sbirrazzuoli, N. ICTAC Kinetics Committee recommendations for analysis of multi-step kinetics. *Thermochim. Acta* **2020**, *689*, 178597. [[CrossRef](#)]
122. Sbirrazzuoli, N. Determination of pre-exponential factor and reaction mechanism in a model-free way. *Thermochim. Acta* **2020**, *691*, 178707. [[CrossRef](#)]
123. Sbirrazzuoli, N. Advanced isoconversional kinetic analysis for the elucidation of complex reaction mechanisms: A new method for the identification of rate-limiting steps. *Molecules* **2019**, *24*, 1683. [[CrossRef](#)]

124. Dowdy, D.R. Meaningful activation energies for complex systems II: Evaluation of the Friedman method when applied to multiple reactions, and comparison with the Ozawa-Flynn-Wall method. *J. Therm. Anal. Calorim.* **1987**, *32*, 1177–1187. [[CrossRef](#)]
125. Doyle, C.D. Kinetic analysis of thermogravimetric data. *J. Appl. Polym. Sci.* **1961**, *5*, 285–292. [[CrossRef](#)]
126. Singh, S.; Patil, T.; Tekade, S.P.; Gawande, M.B.; Sawarkar, A.N. Studies on individual pyrolysis and co-pyrolysis of corn cob and polyethylene: Thermal degradation behavior, possible synergism, kinetics, and thermodynamic analysis. *Sci. Total Environ.* **2021**, *783*, 147004. [[CrossRef](#)] [[PubMed](#)]
127. Kropidłowska, A.; Rotaru, A.; Strankowski, M.; Becker, B.; Segal, E. Heteroleptic cadmium (II) complex, potential precursor for semiconducting CDS layers: Thermal stability and non-isothermal decomposition kinetics. *J. Therm. Anal. Calorim.* **2008**, *91*, 903–909. [[CrossRef](#)]
128. Venkatesh, M.; Ravi, P.; Tewari, S.P. Isoconversional kinetic analysis of decomposition of nitroimidazoles: Friedman method vs Flynn–Wall–Ozawa method. *J. Phys. Chem. A* **2013**, *117*, 10162–10169. [[CrossRef](#)] [[PubMed](#)]
129. Sbirrazzuoli, N.; Vincent, L.; Mija, A.; Guigo, N. Integral, differential and advanced isoconversional methods: Complex mechanisms and isothermal predicted conversion–time curves. *Chemom. Intell. Lab. Syst.* **2009**, *96*, 219–226. [[CrossRef](#)]
130. Friedman, H.L. Kinetics of thermal degradation of char-forming plastics from thermogravimetry. Application to a phenolic plastic. *J. Polym. Sci. Part C Polym. Symposia.* **1964**, *6*, 183–195. [[CrossRef](#)]
131. Huidobro, J.A.; Iglesias, I.; Alfonso, B.F.; Espina, A.; Trobajo, C.; Garcia, J.R. Reducing the effects of noise in the calculation of activation energy by the Friedman method. *Chemom. Intell. Lab. Syst.* **2016**, *151*, 146–152. [[CrossRef](#)]
132. Zubair, M.; Shehzad, F.; Al-Harathi, M.A. Impact of modified graphene and microwave irradiation on thermal stability and degradation mechanism of poly (styrene-co-methyl meth acrylate). *Thermochim. Acta* **2016**, *633*, 48–55. [[CrossRef](#)]
133. Starink, M.J. The determination of activation energy from linear heating rate experiments: A comparison of the accuracy of isoconversion methods. *Thermochim. Acta* **2003**, *404*, 163–176. [[CrossRef](#)]
134. Coats, A.W.; Redfern, J.P. Kinetic parameters from thermogravimetric data. *Nature* **1964**, *201*, 68–69. [[CrossRef](#)]
135. Kissinger, H.E. Reaction kinetics in differential thermal analysis. *Anal. Chem.* **1957**, *29*, 1702–1706. [[CrossRef](#)]
136. Du, J.; Gao, L.; Yang, Y.; Chen, G.; Guo, S.; Omran, M.; Chen, J.; Ruan, R. Study on thermochemical characteristics properties and pyrolysis kinetics of the mixtures of waste corn stalk and pyrolusite. *Bioresour. Technol.* **2021**, *324*, 124660. [[CrossRef](#)]
137. Singh, R.K.; Patil, T.; Sawarkar, A.N. Pyrolysis of garlic husk biomass: Physico-chemical characterization, thermodynamic and kinetic analyses. *Bioresour. Technol. Rep.* **2020**, *12*, 100558. [[CrossRef](#)]
138. Ivanovski, M.; Petrovic, A.; Ban, I.; Goricane, D.; Urban, D. Determination of the Kinetics and Thermodynamic Parameters of Lignocellulosic Biomass Subjected to the Torrefaction Process. *Materials* **2021**, *14*, 7877. [[CrossRef](#)] [[PubMed](#)]
139. Mohomane, S.M.; Motaung, T.E.; Revaprasadu, N. Thermal degradation kinetics of sugarcane bagasse and soft wood cellulose. *Materials* **2017**, *10*, 1246. [[CrossRef](#)] [[PubMed](#)]
140. Criado, J.; Ortega, A. Non-isothermal transformation kinetics: Remarks on the Kissinger method. *J. Non-Cryst. Solids* **1986**, *87*, 302–311. [[CrossRef](#)]
141. Augis, J.A.; Bennett, J.E. Calculation of the Avrami parameters for heterogeneous solid state reactions using a modification of the Kissinger method. *J. Therm. Anal.* **1978**, *13*, 283–292. [[CrossRef](#)]
142. Sbirrazzuoli, N. Is the Friedman method applicable to transformations with temperature dependent reaction heat? *Macromol. Chem. Phys.* **2007**, *208*, 1592–1597. [[CrossRef](#)]
143. Vyazovkin, S.; Sbirrazzuoli, N. Isoconversional kinetic analysis of thermally stimulated processes in polymers. *Macromol. Rapid Commun.* **2006**, *27*, 1515–1532. [[CrossRef](#)]
144. Vyazovkin, S. Some basics en route to isoconversional methodology. In *Isoconversional Kinetics of Thermally Stimulated Processes*; Springer: Cham, Switzerland, 2015; pp. 1–25. [[CrossRef](#)]
145. Sbirrazzuoli, N. Interpretation and physical meaning of kinetic parameters obtained from isoconversional kinetic analysis of polymers. *Polymers* **2020**, *12*, 1280. [[CrossRef](#)]
146. Tony, M.A. Valorization of undervalued aluminum-based waterworks sludge waste for the science of “The 5 Rs’ criteria”. *Appl. Water Sci.* **2022**, *12*, 20. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.