



Bioplastic Production Utilizing Jordanian Zeolite and Kaolin

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Abstract

The study investigates the production of biodegradable plastic films using gelatin as a biopolymer, glycerol as a plasticizer, and natural fillers (Jordanian zeolitic tuff and kaolin) via solution casting method. Key findings demonstrate that incorporating these fillers enhances the films' mechanical properties, biodegradability, and ductility. Increased filler concentration improves film thickness, density, tensile strength (up to 4.97 MPa with kaolin), and toughness while reducing moisture content, solubility, and elongation at break. Biodegradation tests reveal significant weight loss over time, indicating the films' potential for rapid environmental breakdown. The ductility of the films decreases with increasing filler concentration, suggesting enhanced rigidity. These results highlight the potential of utilizing Jordanian natural resources to develop eco-friendly bioplastics with applications in packaging, soil additives, and other industries.

Paper type: Research paper

Key words: biodegradation, bioplastic, waste kaolin, zeolitic tuff

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Introduction

Plastics are widely utilized across various industries, including packaging, automotive, and construction, due to their affordability, versatility, lightweight nature, heat-sealability, and moldability (Mose & Maranga, 2011). However, their extensive disposal as waste poses significant environmental and health challenges, as conventional plastics can take centuries to decompose (Thompson *et al.*, 2009). The over-reliance on petroleum-based plastics has exacerbated these issues, prompting researchers to seek sustainable alternatives.

Bioplastics have gained attention as a promising solution, offering both cost-effectiveness and environmental benefits (Bilo *et al.*, 2018). Derived from renewable resources such as potato starch (Omrani-Fard *et al.*, 2020), corn starch (Marichelvam *et al.*, 2019), cassava starch (Abidin *et al.*, 2021), oils (Yang *et al.*, 2022), and fermentation products like polyhydroxybutyrate (PHB) (Cho *et al.*, 2022), polylactic acid (PLA) (Podkościelna *et al.*, 2022), and polyhydroxyalkanoates (PHA) (Behera *et al.*, 2022), bioplastics are designed to replace traditional petroleum-based plastics. Unlike conventional plastics, they are made from natural materials such as proteins, lipids, and polysaccharides, ensuring improved biodegradability and reducing dependence on fossil fuels (Gonzalez-Gutierrez *et al.*, 2010). Bottom of Form While bioplastics have significant potential for use in diverse industries, including healthcare, food packaging, aerospace, automotive, and cosmetics, further technological advancements are needed to fully realize their capabilities (Muthusamy & Pramasivam, 2019). It is also important to note that plastics can be categorized based on their origin, either fossil-based or bio-based, and their biodegradability, with some being biodegradable and others non-biodegradable. Various research efforts have been made to fabricate bioplastics with enhanced mechanical properties by utilizing a combination of additives and plastic properties. Inorganic nanoparticle additives have been utilized in bioplastic matrices (Amin *et al.*, 2019). This method has exhibited significant effectiveness over several other techniques and has played a crucial role in improving mechanical properties, such as those of kaolin

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(Kwaśniewska *et al.*, 2020) and zeolite (Yang *et al.*, 2022). This study utilizes materials such as zeolitic tuff and kaolin to develop mineral-based bioplastics. Kaolin, a naturally occurring mineral, is extensively used across various industries, including rubber, plastics, and paint, due to its environmental friendliness, cost-effectiveness, and abundant availability (Kwaśniewska *et al.*, 2020). Incorporating kaolin into rubber and synthetic plastics has been demonstrated to enhance water resistance while improving thermal, mechanical, and barrier properties (Kwaśniewska *et al.*, 2020). In contrast, zeolitic tuffs are commonly employed as inorganic fillers in polymer composites, particularly for adsorption and desorption applications (Yang *et al.*, 2022). These microporous aluminosilicate materials are characterized by their high porosity, well-defined pore structures, and large surface areas, making them highly advantageous for such applications. Thus, this study aims to prepare minerals-based bioplastics utilizing Jordanian zeolitic tuff and kaolin as additives to improve the mechanical, structural, and environmental properties of bioplastics. The research focuses on leveraging locally available resources to create eco-friendly alternatives to traditional plastics. Potential applications of these bioplastics include packaging materials, agricultural soil additives, and components for sustainable construction. These applications are particularly relevant in industries seeking to reduce reliance on petroleum-based plastics while maintaining functionality and biodegradability.

2. Materials and Methods

2.1 Materials

- Zeolitic Tuff (ZT): Sourced from Aritain, Jordan, and processed by crushing, sieving, and drying. Sieving was performed into specific fractions (<250 μ m) to ensure uniformity.
- Kaolin: Sourced from the Batn El-Ghul and En Naqb areas in Jordan. Samples were finely ground and sieved (<250 μ m) to achieve consistency.
- Other Components: Gelatin (99% purity) and glycerol (99% purity) were procured from AZ Chem

2.2 Experimental setup and procedure

A schematic representation of the experimental setup is depicted in **Figure 1**. The system comprises a hot plate equipped with a temperature controller, an overhead stirrer, and a beaker. Initially, the beaker was filled with 150ml of distilled water and positioned on the hot plate. Subsequently, 15g of glycerol was added. Once the temperature reached 70°C, 50g of gelatin was introduced, and the mixer was activated to gently stir the solution until it reached 95°C. To minimize bubble formation, the beaker was transferred to an incubator. The mixture was then poured onto a square Teflon sheet mold and allowed to dry, forming the blank sample. For samples containing filler materials, the preparation process was slightly modified. After adding gelatin, fillers such as zeolite tuff or kaolin were incorporated into the solution at varying concentrations while stirring. Once the temperature reached 95°C and the mixture achieved uniformity, the content of the beaker was poured into the prepared mold. The mold, a square plate measuring 20 cm \times 20 cm with a 2 mm edge height, was then allowed to cool to room temperature, enabling the formation of the desired product.

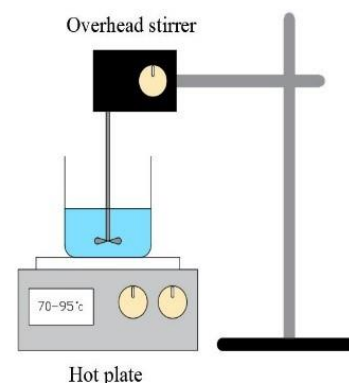


Fig. 1 Experimental setup consisting of a hot plate with temperature controller, overhead stirrer, and beaker

2.3 Procedure for determining the moisture content

To determine the water content within the bioplastic structure, samples measuring 3cm in size were prepared and their initial weight recorded. The samples were then placed in an oven set to 105°C and dried for 24 hours. After drying, the final weight of each sample was measured.

2.4 Procedure for determining the thickness

The thickness of the bioplastic films was determined using a Digimatic Micrometer. For each sample, measurements were taken at three distinct points: one at each end and one at the center. The average of these measurements was calculated and reported as the film's thickness.

2.5 Procedure for determining the density

The density of the bioplastic samples, expressed in g/ml, was calculated by measuring the mass (M) in grams and the area (A) in cm² of the bioplastic film with a known thickness (d) in cm.

2.6 Procedure for determining the water solubility

Water solubility reflects a material's capacity to dissolve in water. The process begins by cutting a 2 cm circular disc from each bioplastic sample and drying it in an oven at 105°C for 24 hours. The initial weight is then measured and recorded. The samples are subsequently immersed in 50ml of deionized water and stirred at approximately 120 rpm for 24 hours. After immersion, the samples are removed, dried again in the oven at 105°C for an additional 24 hours, and their final weight is recorded.

2.7 procedure for determining fourier transform infrared spectroscopy (FTIR)

The bioplastic samples were characterized using an FTIR Spectrometer (BRUKER TENSOR II). Each sample was placed directly on the FTIR sensor for analysis. During the process, infrared light was emitted, and the spectrometer measured the frequencies absorbed by the sample. The outcomes were presented as the percentage of light transmission (Kartini *et al.*, 2022).

2.8 Procedure for Determining the Mechanical Properties

The mechanical properties of the bioplastics, including tensile strength, ductility, elastic modulus, and toughness, were assessed in accordance with the ASTM D-638 standard method. The tests were performed using a HILAP PORTUGAL machine (2021) equipped with a 0.5 kN load cell capacity. Dumbbell-shaped bioplastic film specimens were prepared specifically for the tests. Following preparation and drying, the samples were cut into the standard Type IVB shape specified by ASTM D-638 for tensile strength evaluation.

2.9 Procedure for determining soil burial degradation

The biodegradability of the produced bioplastic was assessed in accordance with ASTM D6400. Samples were cut into 2 cm dimensions and buried in soil for a period of four weeks. Weight loss was measured over time, considering both the exposure duration to sunlight on the soil surface and the internment time in the soil.

2.10 Procedure for determining the chemical and mineralogical characterization

The chemical composition of the ZT and kaolin samples was analyzed using a Wavelength Dispersive Sequential X-Ray Fluorescence (XRF) spectrometer, model Philips PW1404. The spectrometer was operated using the Philip X40 software for precise control and data acquisition.

3. Results and Discussion

3.1 Characterization of filler materials

3.1.1 Chemical Analysis

The chemical composition of the filler materials, determined through XRF analysis, is summarized in Table 1. For ZT, the predominant metal oxides identified include SiO_2 , Fe_2O_3 , Al_2O_3 , CaO, MgO, TiO_2 and K_2O . For kaolin material, the major metal oxides present in the sample are Al_2O_3 , SiO_2 , K_2O , TiO_2 and Fe_2O_3

Table 1. XRF analysis of filler materials (zeolitic tuff and kaolin)

Component	Zeolitic Tuff (wt %)	Kaolin (wt %)
Na_2O	1.64	-
MgO	7.649	0.79
Al_2O_3	11.75	24.55
SiO_2	40.7	58.84
P_2O_5	0.529	0.01
SO_3	0.0823	-
K_2O	2.393	3.91
CaO	11.62	0.27
TiO_2	4.401	1.52
Cr_2O_3	0.0519	-
MnO	0.24	0.01
Fe_2O_3	18.67	1.61
NiO	0.0609	-
CuO	0.0225	-
ZnO	0.0219	-
SrO	0.123	-
ZrO_2	0.0357	-
LOI		8.59

3.2 Bioplastic film thickness

Figure 2 illustrates the change in thickness of the produced bioplastic as a function of mineral concentration. For zeolitic tuff, the thickness increased from 1.25 mm to 1.28 mm with rising concentration, indicating a strong adhesion between the zeolitic tuff particles and the bioplastic matrix. A similar trend was observed when kaolin was used as a filler, with the maximum thickness reaching 1.28 mm at a 0.7 wt% concentration of kaolin. In contrast, the thickness was at its lowest, 1.25 mm, when no kaolin was present. This finding is consistent with the results reported by Tabassum *et al.* (2024), where thickness varied between 0 and 30mm. The observed increase in thickness can be attributed to the relatively large size of the filler particles, which promote a strong integration with the bioplastic matrix.

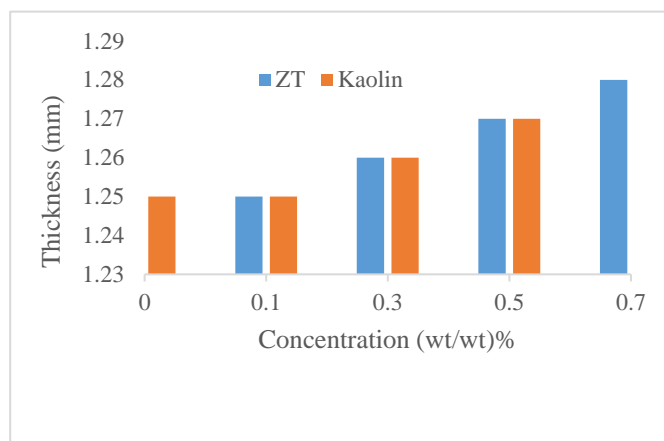


Fig. 2 The thickness of Minerals-based bioplastic at different concentrations of ZT and Kaolin fillers.

3.3 Density

The density of the produced bioplastic using different concentrations of minerals is presented in **Figure 3**. It can be observed that the density of kaolin-based bioplastic increases with increasing concentration of kaolin, the density of kaolin-based bioplastic was found to increase from 0.88 g/ml at 0.1wt% to 1.29 g/ml at 0.7wt%, which agrees with the results reported by Kwaśniewska *et al.*, (2020). The density of the zeolitic tuff-based bioplastic also increased with increasing zeolitic tuff concentration due to the corresponding increase in thickness, from 1.36 g/ml at 0.1 wt% to 1.38 g/ml at 0.7 wt%. This trend is consistent with the findings of previous studies that have shown an increase in density with thickness (Abdullah *et al.*, 2020; Kwaśniewska *et al.*, 2020). The shifts in density can be ascribed to alterations in bioplastic thickness, which correlate with higher contents of ZT and kaolin.

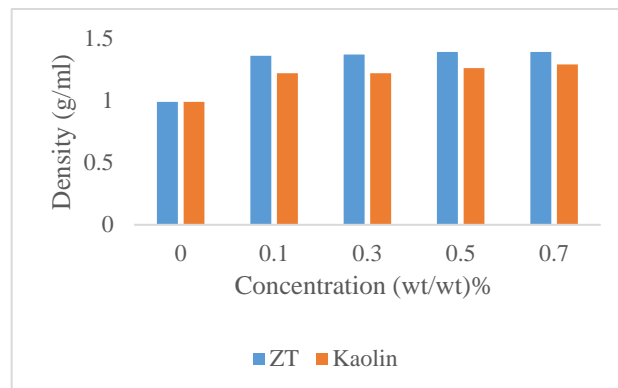


Fig. 3 The density of Minerals-based bioplastic at different concentrations of ZT and Kaolin fillers..

3.4 Water solubility

Water solubility stands as a pivotal parameter, differentiating bioplastics from traditional counterparts like gelatin and starch. This attribute significantly influences the potential applications of bioplastics. Notably, this study maintains constant gelatin content while examining the impact of minerals waste concentration on solubility. Water solubility trends across various bioplastics formulated with diverse concentrations of minerals waste are as illustrated in **Figure 4**. The results revealed that an increase in kaolin concentration has led to a decrease in water solubility, with a reduction from 65% in the blank sample to 45% at 0.1wt% kaolin concentration, and further to 42% at 0.5 and 0.7wt% kaolin concentration. This decrease in solubility was primarily attributed to the hydrophobic nature of kaolin, which, owing to its nanometric size, fills gaps in the bioplastics, enhancing their compactness and water resistance. The addition of kaolin as a reinforcement improved the bioplastics' water resistance, a finding that is consistent with previous reports by Méité *et al.*

(2021). Similarly, an increase in ZT concentration has resulted in a decrease in solubility, with the lowest value observed at 0.7 wt% zeolitic tuff concentration 41% and a solubility value of 43% at 0.1 wt% zeolitic tuffs. The reduction in solubility can be attributed to the interaction between the hydroxyl group in zeolitic tuff-based bioplastics and the molecules of glycerol, which generate strong hydrogen bonds, resulting in a more compact biopolymer matrix and lower water solubility. This finding is corroborated by the results reported by Kartini *et al.* (2022) where the water solubility decreases with increasing filler concentrations

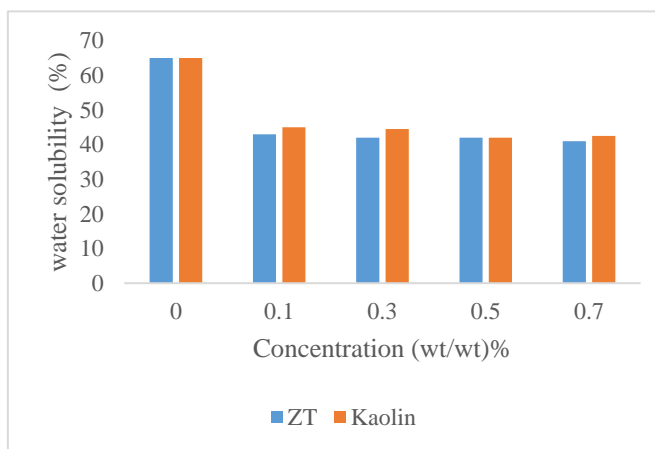


Fig. 4 The water solubility of minerals-based bioplastic at different concentrations of ZT and kaolin fillers..

3.5 Tensile strength

Mechanical properties are critical indicators of bioplastics characteristics. The results presented in **Figure 5** show that the increase in zeolitic tuff concentration has resulted in a corresponding increase in tensile stress. The reinforcement effect of zeolitic tuff was observed to increase the tensile stress from 2.8 MPa for the blank sample to 3.68 MPa at 0.7 wt% of zeolitic tuff. Tensile stress values of 3.3 MPa and 3.4 MPa were obtained at 0.1 wt% and 0.3 wt% of zeolitic tuff, respectively, while the value was 3.61 MPa at 0.5 wt% of zeolitic tuff. This increase in tensile stress can be attributed to the excellent blending between zeolitic tuff and the bioplastic matrix, which results from the

homogenous dispersion of the filler within the matrix. A strong interaction between zeolitic tuff and the bioplastic matrix is expected to occur due to this homogeneous dispersion. Similarly, an increase in kaolin concentration also leads to an increase in tensile stress, with the lowest value observed at 0 wt% of kaolin 2.8 MPa and the highest value of 4.97 MPa at 0.5wt% of kaolin. Tensile stress values of 4.74MPa and 4.76 MPa were obtained at 0.1wt% and 0.3wt% of kaolin, respectively. However, at concentrations above 0.5wt% of kaolin, the value of tensile stress decreases to 3.69 MPa due to agglomeration, aligning with the findings of Kwaśniewska *et al.* (2020) where the tensile strength ranged between 4.23 MPa and 6 MPa. On the other hand, the values obtained in this study are higher than those reported by Najwa *et al.*, (2020). Furthermore, the results surpass those reported by Tuntachon *et al.*, (2019) and Rammak *et al.*, (2021) where the highest tensile stress values were 3.48 MPa and 2.99 MPa, respectively. This indicates the superior mechanical performance of the bioplastic composites developed in this study.

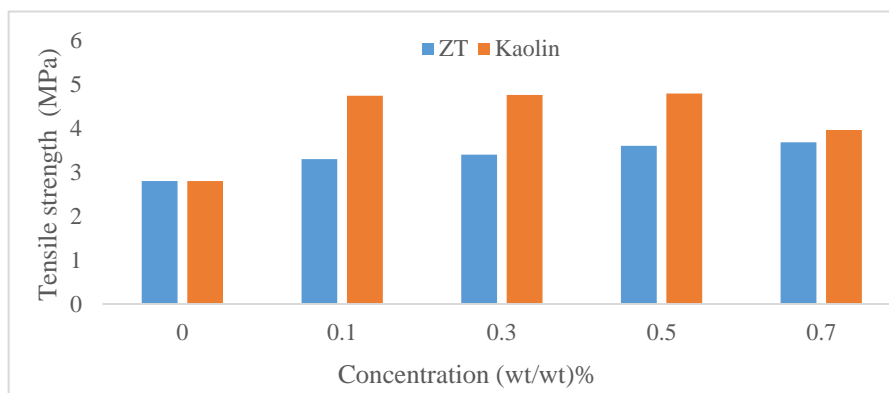


Fig. 5 The tensile strength of minerals -based bioplastic at different concentrations of ZT and Kaolin fillers

3.6 Moisture content vs tensile stress

Figure 6 illustrates the moisture content of kaolin-based bioplastics at various filler concentrations. The results indicate that increasing the kaolin concentration leads to a reduction in moisture content, with the lowest moisture content observed at 0.5 wt% kaolin and the highest at 0 wt%. This can be attributed to the hydrophobic nature of kaolin, which decreases the hydrophilic properties of the bioplastic. As a result, the decrease in moisture content corresponds to an increase in tensile stress, with the highest tensile stress found at 0.5 wt% kaolin. These findings align with previous research by Ojo *et al.*, (2017) who reported moisture content in kaolin samples ranging from 15.00 to 20.82 %. However, the moisture content values in this study were significantly lower than those reported in the literature, suggesting that this bioplastic is well-suited for food packaging applications. The inclusion of reinforcement agents in the bioplastic structure helps to minimize moisture absorption from the surrounding environment, as these agents typically exhibit lower flexibility, a finding that supports the work of Tuntachon *et al.*, (2019).

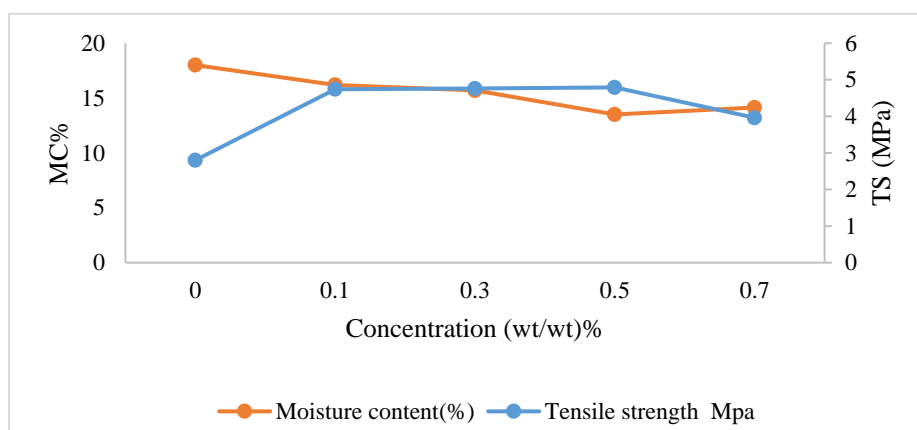


Fig. 6 The relationship between moisture content and the tensile stress at different concentrations of kaolin.

Fig 7. The relationship between moisture content and the tensile stress at different concentrations of kaolin. The moisture content and tensile stress of bioplastic-based zeolitic tuff at different concentrations were examined and presented in **Figure 7**. It was found that the increase in zeolitic tuff concentration has led to a decrease in moisture content, with the highest moisture content observed at 0 wt% of zeolitic tuff and the lowest at 0.7 wt%. These results were supported by the findings of Kartini *et al.* (2022), which showed that the addition of zeolitic tuff in bioplastic reduced its hydrophilicity.

Additionally, increasing the concentration of zeolitic tuff resulted in an increase in tensile stress, with the highest tensile stress observed at 0.7 wt% of zeolitic tuff. Conversely, 0.1wt% of zeolitic tuff showed the highest moisture content but the minimum value of tensile stress. These results align with the characteristics of bioplastic, which become harder with minimal water adsorption, resulting in strong bonds between zeolitic tuff and the bioplastic matrix. Thus, incorporating zeolitic tuff into bioplastic structures can significantly reduce water adsorption from the surrounding environment, leading to improved bioplastic properties. These findings are consistent with Tuntachon *et al.*, (2019) work on the impact of reinforcement agents on water absorption in bioplastics.

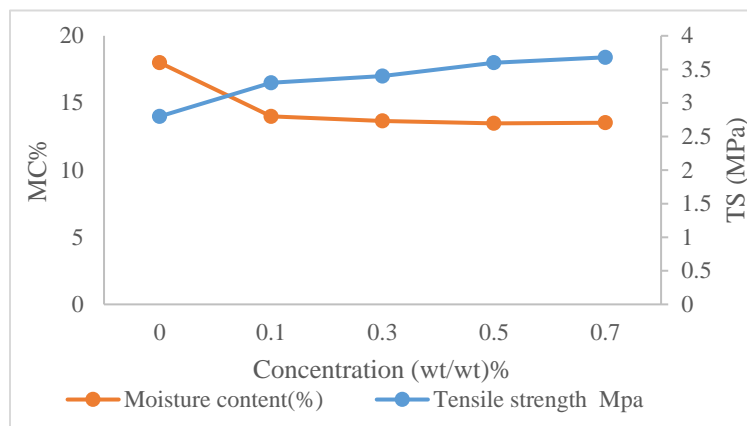


Fig. 7 The relationship between moisture content and the tensile stress at different concentrations of zeolitic tuff..

3.7 Ductility

Ductility, a critical property for determining the suitability of bioplastics in applications such as packaging and transportation, describes the material's capacity to undergo plastic deformation. This property, often measured as elongation at break, is influenced by the volume fraction of the matrix and the distribution of the reinforcing agent. Incorporating a rigid reinforcing compound can mitigate elongation by minimizing stress concentrations.

The ductility values for the produced bioplastics are illustrated in **Figure 8**. The blank sample exhibited a ductility value of 86%. However, increasing the kaolin content led to a reduction in ductility, decreasing from 86% to 55% at a kaolin concentration of 0.5wt%.

Intermediate concentrations of 0.1wt% and 0.3wt% kaolin yielded ductility values of 78.6% and 68%, respectively. Interestingly, a slight rise in ductility was observed at 0.7 wt% kaolin, where the value increased from 55% at 0.5 wt% to 56%. This improvement can be attributed to kaolin precipitation, which enhanced the flexibility of the bioplastic and reduced the strength of the interfacial interactions between kaolin and the matrix. These results are consistent with the findings of Kwaśniewska *et al.*, (2020). Moreover, the ductility values obtained align with those reported by Tabassum *et al.*, (2024) which ranged from 35% to 94%.

For zeolitic tuff, the ductility value decreased as the concentration of zeolitic tuff increased, with the maximum value of ductility achieved at 86% for 0.1 wt% of zeolitic tuff. The ductility value decreased to 80% when the concentration of zeolitic tuff was increased to 0.3 wt%, and further decreased to 80% and 76.8% when 0.5wt% and 0.7wt% of zeolitic tuff were used, respectively. This can be attributed to the strong interfacial action between zeolitic tuff and the bioplastic matrix.

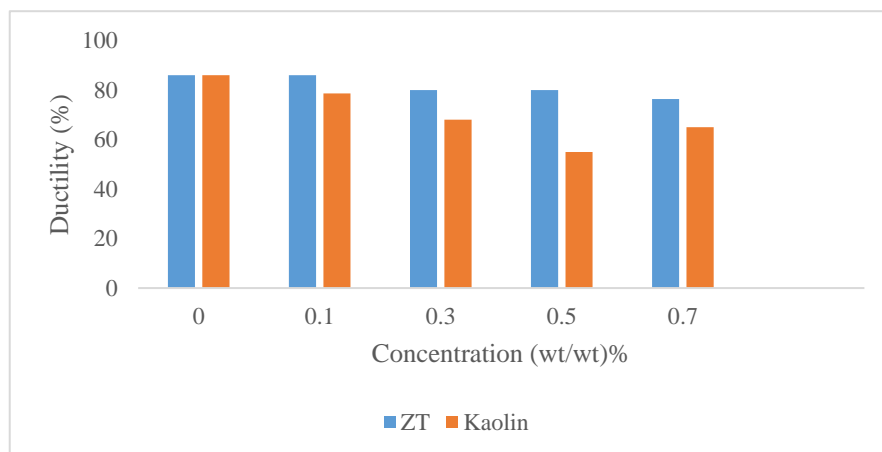


Fig. 8 The ductility value for minerals-based bioplastic at different concentrations of ZT and Kaolin fillers.

3.8 Modulus of elasticity

Figure 9 illustrates the modulus of elasticity for bioplastics with varying concentrations of zeolitic tuff (ZT) and kaolin. The modulus of elasticity is a measure of a material's stiffness, with a lower modulus indicating greater elastic deformation. As shown in the figure, the modulus of elasticity increases with the concentration of kaolin. The highest value was observed at 0.5 wt% kaolin, which can be attributed to the good dispersion of kaolin within the bioplastic matrix. This dispersion promotes the formation of hydrogen bonds between kaolin and the bioplastic, enhancing the material's stiffness. However, at 0.7 wt% kaolin, the modulus of elasticity decreased due to the precipitation of kaolin particles, which reduced intermolecular forces and increased flexibility.

This reduction in stiffness supports the findings of Méité *et al.*, (2021b). Similarly, an increase in the concentration of zeolitic tuff resulted in a higher modulus of elasticity. The lowest elasticity was recorded at 0.1 wt% zeolitic tuff, while the highest value occurred at 0.7 wt%.

3.9 Toughness

The toughness of bioplastic with different concentrations of minerals was investigated, and the results are presented in **Figure 10**. A material's toughness is defined as its ability to absorb energy prior to failure. A material that can withstand higher energy levels before failing is considered tougher than one that cannot. The study found that increasing the concentration of kaolin in bioplastic led to an increase in toughness due to the strong interfacial action between kaolin molecules and the bioplastic matrix. At a concentration of 0.1wt%, the toughness value was the lowest at $4.20\text{J}/\text{m}^3$, while at 0.3wt% and 0.5wt%, the toughness values increased to $4.26\text{J}/\text{m}^3$ and $5.51\text{J}/\text{m}^3$ respectively. At 0.7wt% concentration of kaolin, the toughness value decreased

to $4.95\text{J}/\text{m}^3$ due to kaolin precipitation, resulting in an inhomogeneous internal structure. Increasing the concentration of zeolitic tuff in the bioplastic led to a corresponding enhancement in toughness, attributed to the strong interfacial interaction between zeolitic tuff molecules and the bioplastic matrix. At a concentration of 0.1wt%, the lowest toughness value recorded was $3.18\text{J}/\text{m}^3$. However, as the concentration increased to 0.3wt% and 0.5wt%, the toughness values rose to $3.9\text{J}/\text{m}^3$ and $4.34\text{J}/\text{m}^3$, respectively. The maximum toughness of $4.47\text{J}/\text{m}^3$ was achieved at 0.7wt% zeolitic tuff, which can be explained by greater molecular entanglement and reduced branching within the bioplastic matrix.

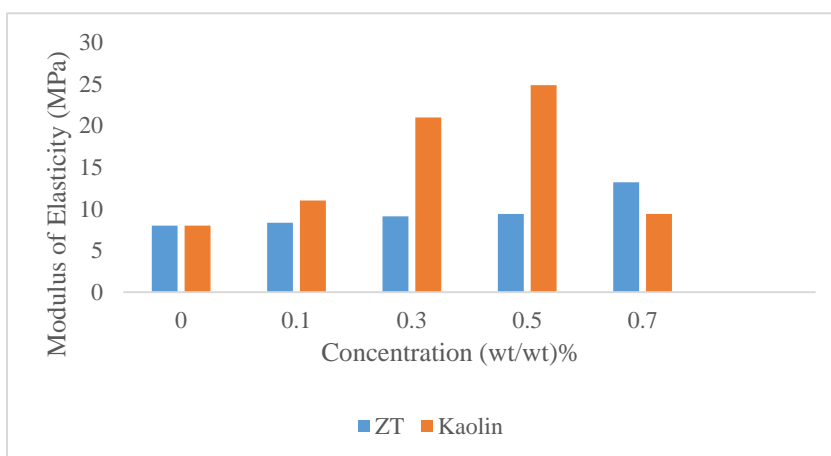


Fig. 9 The elastic modulus of mineral-based bioplastics at different concentrations of the ZT and Kolin fillers.

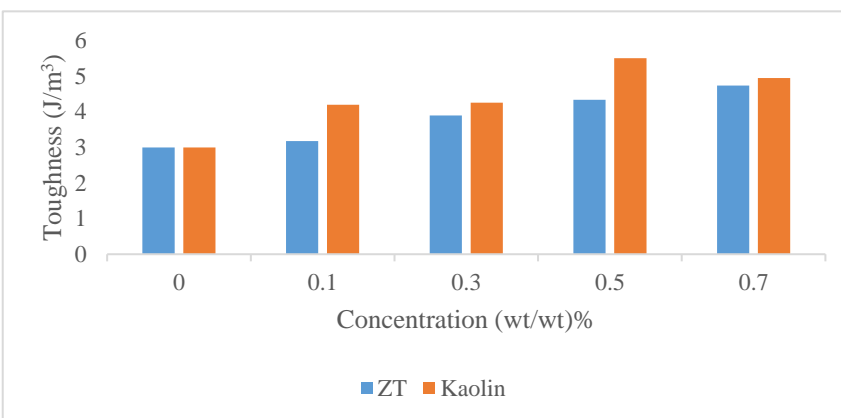


Fig. 10 The Toughness of minerals-based bioplastic at different concentrations of ZT and Kaolin fillers.

3.10 FTIR analysis

Figure 11 presents the FTIR spectra for a blank sample and samples reinforced with zeolitic tuff and kaolin. The intensity of the bands decreased in the mineral-modified samples, which is attributed to the stretching vibration of the C-O group around 1077 cm^{-1} , as shown in Table 2. This reduction indicates the degradation of the polymer chain. The disappearance of a peak at 3227 cm^{-1} in the blank sample, corresponding to O-H and C-H stretching, further supports the breakdown of -C=H bonds (Amri *et al.*, 2018).

When zeolitic tuff was introduced, the -OH peak shifted to a lower wavelength, from 3227 cm^{-1} to 3207 cm^{-1} , and further shifted to 3167 cm^{-1} with the addition of kaolin. These shifts in the -OH stretching vibration suggest that the minerals dispersed well and were compatible with the bioplastic matrix. A peak around 1642 cm^{-1} , attributed to C-C stretching, and another vibration at 1636 cm^{-1} , observed in the FTIR spectrum, imply interactions between the bioplastic matrix and both zeolitic tuff and kaolin, forming intramolecular and intermolecular hydrogen bonds.

The reduction in amorphous nature, evidenced by the decreased intensity of the peak between 724 and 596 cm^{-1} in the zeolitic tuff, kaolin, and titanium samples, further confirms these interactions. The presence of -COOH, OH, and COOH functional groups as flexible active sites in the biodegradable films contributes to faster degradation, as these functional groups enable quicker binding to enzyme sites compared to more rigid films.

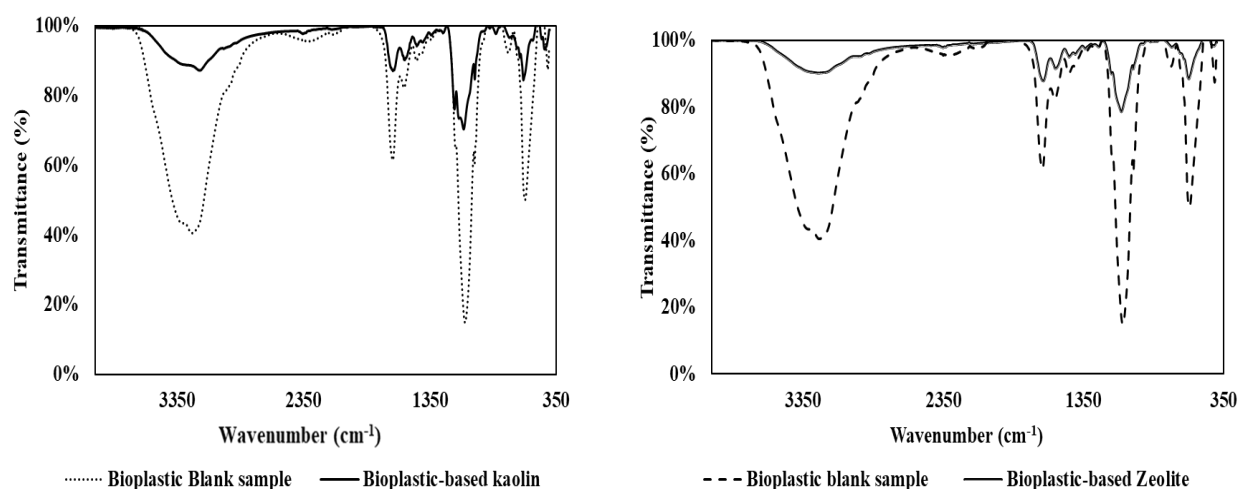


Fig. 11 The FTIR spectra for a blank sample and samples reinforced with ZT and kaolin.

Table 2. Wavenumbers and functional groups found in Minerals-based bioplastic.

Zeolitic tuff		Kaolin	
Wavenumber (cm ⁻¹)	Functional group	Wavenumber (cm ⁻¹)	Functional group
3233.58- 3246.45	OH/CH	3246-3235	O-H/C-H
1635	C-C	1641	C=C
1072	C-O	1026	C-O
500-700	C-H	500-700	C-H

3.11 Biodegradability

The degradation of biodegradable polymers is influenced by fungi, bacteria, and other microorganisms, which break down the polymers through enzymatic or metabolic processes, converting them into smaller molecules. Biodegradable films with flexible active sites, such as $-COOH$, OH , and $COOH$ groups, tend to degrade more quickly as they bind to enzyme sites faster than rigid films. Additionally, shorter-chain polymers degrade more rapidly than longer-chain polymers. The biodegradability of the bioplastic was evaluated under various environmental conditions and temperatures. Initially, the samples were placed in an open container with 150g of soil, maintained at a low temperature and high humidity. **Figure 12** illustrates the biodegradability of the bioplastic at different time intervals, with conditions set at 15°C and 50% humidity. The results indicate a slight increase in biodegradation over time for both kaolin and ZT, with no weight loss after one day. However, a 3% weight loss was recorded after one month, indicating gradual degradation. The biodegradation rate improved with an increasing number of days. Finally, a biodegradability test was performed in a closed container at a high temperature and low humidity. The samples were then placed in an open container containing 150g of soil, maintained at a temperature of 25°C and a humidity level of 30%. As illustrated in **Figure 12**, the biodegradation of the bioplastic samples was monitored over time. When compared to results observed at lower temperatures, it was clear that higher temperatures significantly accelerated the biodegradation process. Over a period of four months, the degradation percentage increased from 6% to 20% for both kaolin and ZT samples. Following this, the samples were transferred to a closed container also containing 150g of soil, where the humidity was adjusted to 40% while the temperature remained stable at 25°C. Within five days, the samples softened from a rigid to a flexible state. After approximately two weeks, complete degradation was observed for both the kaolin and ZT samples. **Figure 13** depicts the condition of the samples after two weeks in the closed container.

Conclusions

This study demonstrates the significant potential of Jordanian zeolitic tuff and kaolin in enhancing the physio-mechanical properties and biodegradability of bioplastics. Incorporating these minerals increased the tensile strength (up to 4.97 MPa with kaolin), density, and toughness of the bioplastics while reducing their moisture content, solubility, and elongation. Biodegradability tests revealed that the addition of these minerals supports faster degradation in controlled environments, making the bioplastics ideal for eco-friendly applications. The findings underscore the suitability of these mineral-based bioplastics for applications such as food packaging, agricultural soil additives, and other industrial uses where sustainability and biodegradability are paramount. Furthermore, the use of locally available Jordanian resources offers an economically viable and environmentally conscious alternative to synthetic plastics. Future research should focus on scaling up production processes, investigating the compatibility of these bioplastics with various additives, and exploring additional applications in medical-grade bioplastics, construction materials, and other sustainable technologies. Long-term environmental impact assessments and economic feasibility studies should also be conducted to solidify the industrial viability of these bioplastic composites.

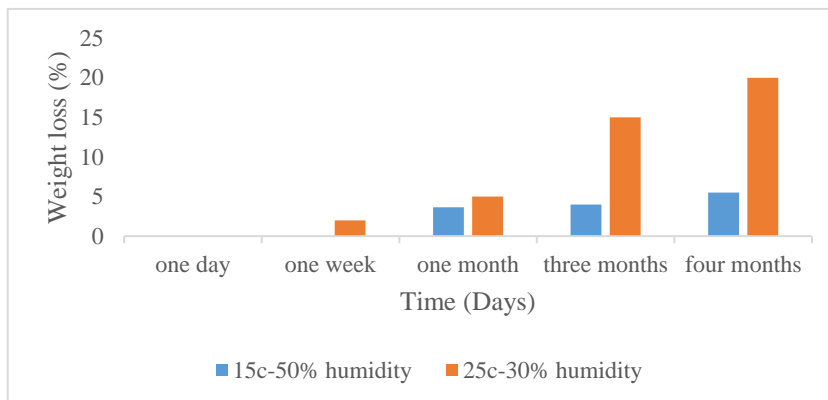


Fig. 12 Biodegradability of mineral-based bioplastic with zeolitic tuff and kaolin at different conditions (15°C - 50% humidity and 25°C - 30% humidity).



Fig 13. Biodegradability test (a) Kaolin sample before poured in soil. (b) Kaolin sample after two weeks

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Nomenclature

d	= density	[g/ml]
M	= mass	[g]
A	= area	[cm ²]
TS	= tensile strength	[MPa]
T	= Thickness	[mm]
MC	= Moisture Content	[%]
WS	= Water Solubility	[%]
E	= Elastic Modulus	[MPa]
D	= Ductility	[%]
Tf	= Toughness	[J/m ³]

8. References

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