



The influence of plastic mulch degradation on microplastic contamination in agricultural soils under different climatic conditions

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ARTICLE INFO

Keywords:

Agricultural sustainability
Chemical functional group
Polyethylene
Soil pollution

Article history

Submitted: 2025-03-17

Revised: 2025-05-12

Accepted: 2025-07-25

Available online: 2025-11-13

Published regularly:

December 2025

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ABSTRACT

Plastic mulch is widely used in agriculture to improve crop productivity by regulating soil temperature, retaining moisture, and suppressing weed growth. However, its degradation produces microplastics that can accumulate in the soil, disrupt microbial communities, and potentially enter the food chain. This study examines microplastic contamination in agricultural soils under different climatic conditions: Bogor (humid) and Lombok (hot and dry). Various analytical techniques were employed to characterize material degradation, including FTIR spectroscopy, SEM, UV-Vis, and thermal conductivity measurements. The results show that differences in climate and environmental factors, such as high temperature, UV exposure, and microbial activity, can accelerate mulch degradation, resulting in higher microplastic concentrations in Lombok (455 ± 57.74 particles kg^{-1}) compared to Bogor (265 ± 43.59 particles kg^{-1}). FTIR analysis confirmed the presence of oxidation-derived functional groups (C=O, O-H). Thermal analysis indicated a decrease in the material's thermal conductivity, UV-Vis revealed increased polymer chain scission, and SEM showed significant surface degradation. These findings highlight the environmental risks of plastic mulch use and underscore the importance of adopting more sustainable alternatives to reduce microplastic pollution in agricultural soils.

How to Cite: Azima, M. F., Kurniati, M., Irmansyah, Umam, R. (2025). The influence of plastic mulch degradation on microplastic contamination in agricultural soils under different climatic conditions. *Sains Tanah Journal of Soil Science and Agroclimatology*, 22(2), 395-409. <https://doi.org/10.20961/stjssa.v22i2.100546>

1. INTRODUCTION

Plastic mulch has become an integral component of modern agricultural practices due to its ability to enhance crop productivity through several critical mechanisms. As a covering material applied on agricultural soil surfaces, plastic mulch helps retain soil moisture, regulate temperature, suppress weed growth, and improve fertilizer use efficiency. These benefits are especially crucial in regions where climatic variability poses challenges to sustainable farming. The widespread adoption of plastic mulch as a tool for increasing yield, conserving water, and mitigating stress on crops (Mansoor et al., 2022). However, while the short-term advantages of plastic mulch are well-documented, the long-term environmental consequences associated with its degradation remain a pressing concern.

The predominant material used in plastic mulch is polyethylene, a synthetic polymer known for its durability and chemical stability. Ironically, the very properties that make polyethylene effective in agricultural applications—its

resistance to degradation, lightweight structure, and low cost—also contribute to its persistence in the environment. Polyethylene does not readily break down through natural processes, which leads to the gradual accumulation of plastic residues in the soil over repeated growing seasons (Somanathan et al., 2022). As the mulch undergoes environmental stress, including UV radiation from sunlight, wide temperature fluctuations, and repeated mechanical disturbances from tilling and harvesting, it begins to fragment into smaller particles. These fragments, often smaller than 5 millimeters, are referred to as microplastics.

Microplastics are increasingly recognized as emerging contaminants in terrestrial ecosystems, especially in agricultural soils. The formation of microplastics from plastic mulch presents a silent yet significant threat to soil health (Qiang et al., 2023; Xie et al., 2025). Unlike organic matter that decomposes and contributes to soil fertility, microplastics persist and accumulate, potentially altering soil

structure and porosity. This disruption can impede water infiltration and retention, two factors essential for maintaining healthy plant roots. Furthermore, microplastics can interact with soil microorganisms, affecting microbial biomass, enzyme activity, and the overall functioning of the soil food web. These changes, while subtle in the short term, may have profound consequences over time, threatening the sustainability of agricultural ecosystems.

The resilience of microplastics to natural degradation processes raises additional concerns. Once incorporated into soil, microplastics may remain for decades without significant decomposition, particularly in regions with low biological activity or extreme environmental conditions (Abbate et al., 2023). Their interaction with other soil pollutants—such as pesticides, heavy metals, or excess fertilizers—can create synergistic toxic effects that further degrade soil quality. Therefore, addressing the proliferation of microplastics is not merely a matter of waste management but a crucial step toward ensuring long-term soil sustainability and food security (Miao et al., 2023). A number of studies have examined how plastic mulch breaks down in soil environments. It is now widely understood that this degradation is driven by a combination of physical, chemical, and biological processes (Rahim et al., 2022; Wang et al., 2023). Physically, mechanical fragmentation from agricultural machinery or trampling by humans and animals contributes to the breakdown of the material. Chemically, the process of oxidation—particularly photooxidation initiated by sunlight—alters the polymer structure, making it more brittle and susceptible to fragmentation (Sang et al., 2020). Biologically, soil microbes in certain conditions are capable of producing enzymes that can degrade plastic polymers, although this process is slow and highly dependent on environmental factors such as moisture and temperature (Broda et al., 2024; En-Nejmy et al., 2025).

Interestingly, climatic conditions play a pivotal role in modulating the rate and nature of plastic degradation. In regions like Lombok, where the climate is characterized by high solar radiation, limited rainfall, and elevated temperatures, photodegradation and thermal breakdown dominate. The intense UV exposure accelerates the oxidation of plastic mulch, leading to faster physical disintegration. In contrast, Bogor—located in a more humid region with moderate temperatures and frequent rainfall—offers conditions favorable to microbial activity. The consistent moisture and biologically active soils enhance the potential for biotic degradation mechanisms. As highlighted by Rahim et al. (2022), such climatic contrasts underscore the need for localized assessments of plastic degradation, as generalizing degradation behavior across regions may lead to inaccurate risk assessments.

However, detailed comparative studies on how plastic mulch degrades under different climatic conditions are still limited. While global trends have been identified, region-specific investigations are essential for developing appropriate mitigation strategies. For instance, in areas where photodegradation dominates, alternative materials with UV-blocking properties or biodegradable options might be more appropriate. Conversely, in biologically active soils, strategies that enhance microbial degradation could be explored. Additionally, the environmental fate of microplastics extends beyond mere presence in soil. Research by Olesen et al. (2017) and Salama and Geyer (2023) emphasizes that microplastics can bind with other organic and inorganic pollutants, affecting their mobility and bioavailability. These interactions can result in complex pollutant mixtures that are harder to manage and remediate. Furthermore, as microplastics accumulate, they may reach deeper soil layers or even leach into groundwater systems, posing risks to broader environmental and human health.

To address this knowledge gap, the current study investigates the degradation of plastic mulch and its resulting microplastic contamination in two contrasting agricultural regions: Bogor in West Java, Indonesia, and Lombok in West Nusa Tenggara. These two regions serve as ideal case studies due to their distinct climatic characteristics—Bogor being humid and biologically rich, while Lombok is drier with stronger sunlight and higher temperatures. The objective is to explore how different climatic conditions influence the degradation pathways of plastic mulch and the subsequent formation of microplastics in soil.

To achieve this, the study employs a suite of advanced analytical techniques. Fourier-transform infrared spectroscopy (FTIR) is used to detect changes in the chemical bonds of the polymer. Scanning electron microscopy (SEM) provides visual evidence of physical degradation, such as cracking and surface roughness. UV-Visible spectrophotometry helps assess photooxidation effects, while thermal conductivity analysis reveals alterations in the mulch's material properties over time. Through these methods, the study aims to provide a comprehensive understanding of how plastic mulch degrades in situ under real-world farming conditions.

By comparing findings across both regions, this research contributes to the growing body of knowledge on microplastic contamination in soils. It also offers critical insights for policymakers, farmers, and environmental scientists seeking to balance agricultural productivity with environmental stewardship. Ultimately, it underscores the urgent need to rethink the use of conventional plastic mulches and to develop more sustainable alternatives tailored to specific agroecological zones.

Table 1. Characteristics of the Agricultural Study Sites

Location	Climate Type	Average Temperature (°C)	Humidity (%)	Dominant Soil Type	Cultivated Crop
Bogor (Cikabayan Farm)	Humid tropical	26-28	80-90	Andosol	Tomato (<i>Solanum lycopersicum</i>)
Lombok (Suralaga)	Hot and semi-arid	30-33	50-60	Regosol	Chili (<i>Capsicum annum</i>)

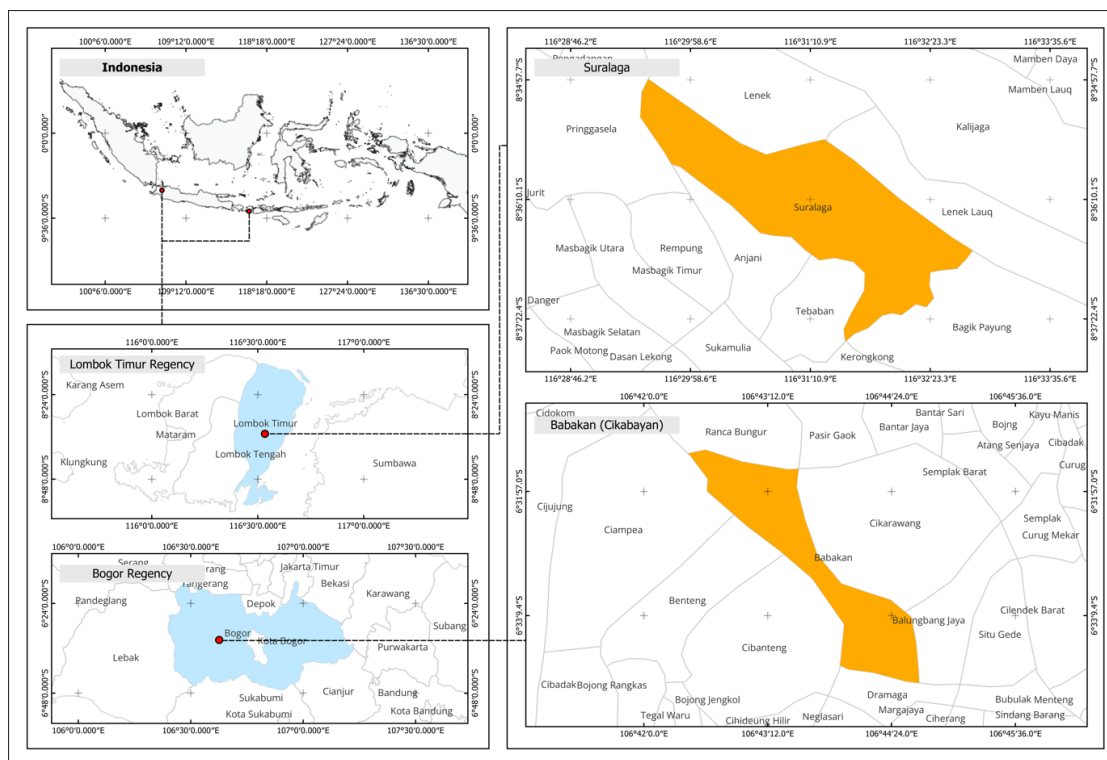


Figure 1. Research locations map

2. MATERIAL AND METHODS

The study was conducted from January to December 2024 in two agricultural sites representing contrasting climatic zones in Indonesia: Cikabayan, Bogor (humid tropical climate) with location coordinate 6.55214906461462° S, 106.71871207588052° E, and Suralaga, East Lombok (hot semi-arid climate) with coordinate 8.596449° S, 116.522031° E. Bogor features an average annual temperature of 26–28 °C, high rainfall, and andosol soils, while Lombok exhibits higher temperatures (30–33 °C), low seasonal rainfall, and regosol soils with low organic matter content (Table 1). These locations (Fig. 1) were selected to examine how environmental conditions influence plastic mulch degradation and microplastic generation in soil. Samples were collected for analysis performed at various laboratories, including the National Research and Innovation Agency (BRIN) Physics Imaging Laboratory in Serpong, Biofarmaka Laboratory, and the Oceanography Laboratory at IPB.

2.1. Materials

The primary experimental material was a commercially available black polyethylene (PE) mulch film with a nominal thickness of 0.03 mm, widely used by local farmers in both study regions. The mulch was deployed at the onset of the cropping season, following standard agronomic procedures, and remained in place for three months. In addition, a control sample of unused polyethylene mulch was analyzed alongside field-exposed samples to serve as a baseline reference for comparison. This control allowed clear identification of structural and chemical changes attributable to environmental exposure. The control sample exhibited smooth morphology, lower thermal conductivity, and no significant oxidation-related functional groups, confirming that the degradation observed in the field samples was due

to combined environmental factors rather than manufacturing defects (Narloch et al., 2022).

All field and laboratory procedures were conducted using pre-cleaned, contamination-free equipment and glassware to minimize the risk of extraneous microplastic introduction. Three months duration was selected to reflect a typical early-stage cultivation cycle commonly practiced in Indonesian agriculture and corresponds to the early crop cycle (seedling to vegetative stage) when mulch usage is most intensive. During this stage, the use of plastic mulch plays a crucial role in stabilizing soil temperature, retaining moisture, and minimizing weed competition, all of which contribute to optimizing root zone conditions for seedling establishment (Salama & Geyer, 2023).

2.2. Experimental design and sampling protocol

Soil sampling was conducted at the end of the cropping season, following a three-month period of plastic mulch application. At each site, 4 independent soil samples were collected from the surface layer (0–10 cm) using a stainless steel spatula to minimize the risk of contamination (Nguyen et al., 2025). Each soil sample was obtained from a separate, randomly selected location within the agricultural plot to ensure spatial representativeness and to serve as a biological replicate (Yang et al., 2024).

For each sampling point, approximately 50 grams of soil were collected and immediately transferred into pre-cleaned glass containers. The use of glassware and metal tools was strictly maintained throughout the sampling and storage process to prevent the introduction of extraneous microplastic particles (J. Zhang et al., 2025). All samples were clearly labeled, transported to the laboratory, and air-dried at room temperature in a clean environment prior to analysis (Narloch et al., 2022).

2.3. Microplastic extraction and quantification

Microplastics were extracted from 50 g aliquots of dried soil using a density separation protocol with saturated sodium chloride (NaCl) solution (Hudson et al., 2023; Noor-ul-Ain et al., 2022). The soil-saline suspension was vigorously agitated and allowed to settle, after which the supernatant was filtered through 0.45 µm pore size membrane filters (Dong et al., 2025; Pahlawan et al., 2025). The retained particles were carefully transferred to petri dishes and examined under a stereomicroscope. Microplastics were identified based on morphological criteria (shape, color, and texture), counted, and measured for size distribution (1–5 mm) using calibrated image analysis software (Ju et al., 2025; Y. Wang et al., 2025). Procedural blanks and negative controls were included in each batch to monitor potential laboratory contamination. Microplastic abundance was recorded as the number of particles per 50 grams of dry soil and extrapolated to an estimated number of particles per kilogram for comparative purposes using Equation 1.

$$\text{Microplastic concentration} = \frac{\text{particle count}}{\text{sample mass (g)}} \times 1000 \dots \dots \dots [1]$$

This protocol was consistently applied at both study locations, yielding a total of four replicates per site. The resulting data provided quantitative measures of microplastic contamination in agricultural soils, enabling robust statistical comparison between the two contrasting environments. Microplastics were then filtered and subjected to infrared spectroscopy for the identification of functional groups (Miao et al., 2024).

2.4. Analytical techniques and instrumentation

The experimental procedures included several analytical techniques to study the degradation and microplastic contamination of polyethylene (PE) plastic mulch in soil. The instruments used consisted of:

- Fourier Transform Infrared Spectroscopy (FTIR): Bruker Tensor II (4000–400 cm⁻¹, 4 cm⁻¹ resolution, attenuated total reflectance mode) for chemical functional group identification. Instrument calibration was performed using certified polystyrene film before each session (Villegas-Camacho et al., 2024). The obtained spectra were compared with standard reference spectra of virgin and weathered polyethylene to confirm the presence of degradation-related functional groups (Sandt et al., 2021). Each sample was scanned three times to ensure spectral consistency, and spectral noise was minimized by baseline correction and normalization (Mecozzi et al., 2016; X. Wang et al., 2025).
- Thermal Conductivity Meter: Kemtherm QTM-D3 (0.2–20 W/m·K, ±5% accuracy, temperature range 10–50°C) for thermal conductivity analysis (Kumar et al., 2017). Calibration was carried out using reference materials with known conductivity values within the target measurement range. Each sample was measured three times under the same temperature and contact pressure conditions to reduce variability. The device was allowed to stabilize before each reading to ensure thermal equilibrium.

- Soil Thermometer: The thermometer was calibrated against a mercury standard thermometer before use. Soil temperature measurements were taken on the surface of plastic mulch and times (hourly from 06:00 to 18:00) over a seven-day period to reduce diurnal variability (Romano et al., 2024; Xie et al., 2023). The device was cleaned before each insertion to prevent cross-contamination between sites.
- Ultraviolet-Visible Spectroscopy (UV-Vis): Hitachi UH5300 (190–1100 nm, deuterium & tungsten-halogen sources, 1 cm quartz cuvette) for optical properties measurement (Chong et al., 1997). The UV-Vis instrument was calibrated using standard solutions to ensure wavelength accuracy and photometric stability. Quartz cuvettes were cleaned with ethanol and deionized water before each measurement (Marczak-Grzesik et al., 2025). Each sample was analyzed in triplicate, and spectra were cross-compared to confirm trends in UV absorbance degradation patterns (Klempová et al., 2023). The molar absorptivity coefficient (ε) is a key parameter in spectrophotometry that indicates how strongly a substance absorbs light at a specific wavelength. It is determined using the Beer-Lambert law in Equation 2.

$$A = \epsilon \times c \times l \dots \dots \dots [2]$$

Where A is absorbance (au), c is concentration (mol L⁻¹), l is path length (cm), and ε is molar absorptivity (L mol⁻¹·cm⁻¹) (Fajri et al., 2024). In polyethylene (PE) plastic analysis, UV-absorbing compounds are extracted into a solvent and analyzed using UV-Vis spectrophotometry. Absorbance values are then used to calculate ε based on known extract concentration and cuvette length (Nugraha et al., 2023).

- Scanning Electron Microscope (SEM): Thermo Fisher Apreo 2 (1.2 nm resolution, 0.5–30 kV voltage, up to 1,000,000 × magnification) for morphology observation. SEM imaging was conducted using standardized settings (e.g., accelerating voltage, magnification, beam intensity) (Chou et al., 2022; Okubo et al., 2025). The same imaging parameters were applied to all samples to allow valid comparisons. Surface areas for imaging were selected based on consistent criteria, and image quality was verified for resolution and contrast.

The combination of procedural controls, instrument calibration, triplicate measurements, and comparison with reference standards enhanced the robustness and credibility of the analytical data obtained in this study.

3. RESULTS

3.1. Microplastic concentration analysis

Microplastic analysis in soil is essential to understanding the impact of plastic mulch degradation under varying environmental conditions. The high-density flotation method has been effectively employed to isolate and quantify microplastics from soil matrices (Miao et al., 2024). As shown in Tables 2 and 3, there is a significant difference in microplastic particle counts between the two study sites with contrasting climates. In the Cikabayan agricultural field (Bogor), which is characterized by a humid tropical climate and andosol soil type, the average concentration of microplastics was 265 ± 43.59 particles kg⁻¹.

Table 2. Microplastic particles from 50-gram soil samples in Cikabayan, Bogor

Replication	Particles/50 grams	Estimated particles kg ⁻¹
1	10	200
2	14	280
3	16	320
4	13	260
Average	13.25	265
Standard deviation (±)		43.59

Table 3. Microplastic particles from 50-gram soil samples in Suralaga, East Lombok

Replication	Particles/50 grams	Estimated particles kg ⁻¹
1	19	380
2	24	480
3	26	520
4	22	440
Average	22.75	455
Standard deviation (±)		57.74

In contrast, the agricultural site in Suralaga (East Lombok), with a semi-arid climate (low to moderate rainfall) and regosol soil, exhibited a higher average concentration of 455 ± 57.74 particles kg⁻¹ (Table 4). This disparity is primarily influenced by environmental factors such as temperature,

humidity, and soil characteristics, which affect the rate and extent of plastic mulch degradation (Hou et al., 2019; Yu et al., 2025). The drier conditions and elevated temperatures in Lombok likely accelerated the fragmentation of polyethylene mulch, resulting in a higher release of microplastic particles compared to the Bogor site (Bo et al., 2023; Ryu et al., 2025). In addition to these abiotic factors, microbial activity plays a critical role in the degradation process. Soil microorganisms—particularly bacteria and fungi—can colonize plastic surfaces and secrete enzymes that initiate bio-fragmentation (Peksen et al., 2023; Yang et al., 2025). This microbial degradation often acts synergistically with photodegradation and thermo-oxidative mechanisms, collectively weakening the polymer structure and facilitating microplastic formation (Nguyen et al., 2025).

Furthermore, as indicated in Table 4, the relatively wide range and 95% confidence intervals at both locations reflect the spatial variability of microplastic distribution within the 10 cm topsoil layer (Bai et al., 2024; J. Zhang et al., 2023). This variation is expected, given that sampling was conducted randomly across multiple points to account for field heterogeneity (Jemec Kokalj et al., 2024; Salama & Geyer, 2023). The use of descriptive statistics—including mean, standard deviation, range, and confidence intervals—provides a comprehensive overview of microplastic contamination levels and supports the reliability of the estimates at each study site (Sintim et al., 2020; Yang & Gao, 2022).

Table 4. Descriptive statistics of microplastic quantity (particles kg⁻¹ soil) in Cikabayan, Bogor, and Suralaga, East Lombok

Location	Mean (particles/kg)	SD (±)	Range (particles kg ⁻¹)	95% CI (particles kg ⁻¹)
Cikabayan, Bogor	265	43.59	120	195.65 – 334.35
Suralaga, East Lombok	455	57.74	140	363.17 – 546.86

Table 5. FTIR's functional groups analysis

Wavenumber (cm ⁻¹)	Functional Group	Control	Bogor	Lombok	Description
3700 – 3500	O-H Stretching (Alcohol/Carboxylic Acid)	None	Very weak	Weak	Slight adsorption of water or carboxylic acid formation due to PE degradation (Belhachemi et al., 2022)
2950 – 2849	C-H Stretching (Asymmetric, Symmetric, Aliphatic)	Present	Present	Present	Typical characteristics of polyethylene (PE), no significant change (Baharuddin et al., 2023)
1715	C=O Stretching (Carbonyl)	None	Present	More clear	Polymer oxidation due to UV exposure or environmental factors (Miao et al., 2024)
1465 – 1460	CH ₂ Bending (Deformation)	Present	Present	Present	Basic chain structure of PE remains intact (Baharuddin et al., 2023)
1250 – 1000	C-O Stretching (Alcohol/Ester)	None	More clear	More clear	Oxidative degradation or ester formation due to environmental exposure (Wang et al., 2023)
750 – 700	C-Cl Stretching	None	Weak	More clear	Environmental contamination or reaction with chlorine from the Lombok environment (Somanathan et al., 2022)
600 – 550	CH ₂ Rocking (Crystalline Polymer)	Present	Present	Present	Typical PE characteristic indicating basic polymer structure is intact (Baharuddin et al., 2023)

3.2. FTIR analysis

In plastic degradation studies, Fourier-transform infrared (FTIR) spectroscopy is widely used to detect structural changes in polymers resulting from photo-oxidative, thermal, or chemical degradation. One of the most prominent indicators of oxidative degradation is the emergence of carbonyl (C=O) functional groups, typically observed as a peak around 1700 cm^{-1} in the FTIR spectrum (Sang et al., 2020). This carbonyl peak is associated with oxidative processes, in which exposure to UV radiation or heat initiates reactions between oxygen and the polymer chains, resulting in the formation of detectable carbonyl groups (Maiket et al., 2025). In this study, the extent of mulch plastic degradation was assessed based on the intensity of carbonyl peaks observed in the FTIR spectra of three different samples (Merino et al., 2022; Ryu et al., 2025).

The FTIR spectra compare the chemical characteristics of the mulch samples from the control, Bogor, and Lombok sites (Fig. 2). Differences in intensity across various spectral regions indicate functional group transformations due to environmental degradation during field use. Increased absorbance in the range of $3500\text{--}3200\text{ cm}^{-1}$ suggests the formation of hydroxyl (–OH) groups as a result of oxidative degradation, with the Lombok sample showing the highest intensity (Merino et al., 2019; Senevirathne et al., 2025). In the $1750\text{--}1650\text{ cm}^{-1}$ region, elevated absorbance corresponds to the formation of carbonyl (C=O) groups caused by photo-oxidation or thermal degradation (Yang et al., 2025; Yang et al., 2024). The Lombok sample exhibited a higher carbonyl intensity than the Bogor sample, indicating a greater extent of degradation (Cunsolo et al., 2021). A comprehensive identification of detected functional groups is provided in Table 5.

Decreased intensity within the fingerprint region ($1500\text{--}1000\text{ cm}^{-1}$) indicates molecular structure modifications resulting from environmental exposure, such as polymer chain scission and the formation of new compounds. These spectral variations reflect the differing environmental

conditions at each site (Belhachemi et al., 2022; Sang et al., 2020). The Lombok sample experienced the most pronounced degradation due to higher temperatures and UV intensity compared to the Bogor. In contrast, the control sample maintained stronger spectral intensities, indicating a more intact material (Sandt et al., 2021). The FTIR spectra clearly demonstrate that the location of mulch application affects the extent of plastic degradation, with the highest degradation observed in the Lombok sample, followed by Bogor, and then the control (Junga et al., 2024).

Figure 3 and Figure 4 also show that the microplastic samples obtained from both locations (Bogor and Lombok) exhibit the characteristic "fingerprint region" spectrum of polyethylene, indicating that the microplastics found at both sites are fragments or breakdown products of polyethylene plastic mulch. Plastic degradation reduces both the quality and mechanical strength of the mulch, shortening its functional lifespan in agricultural applications. Degraded plastic loses its ability to retain soil moisture and protect crops, while simultaneously increasing the risk of environmental microplastic contamination (Olesen et al., 2017).

3.3. Thermal conductivity analysis

The thermal characterization in this study demonstrated that the thermal conductivity of plastic mulch increased following field application, particularly in locations with higher average daily temperatures, such as the agricultural site in Suralaga, East Lombok. As illustrated in Figure 5, the average daily temperatures in Suralaga consistently exceeded those in Cikabayan, Bogor, with daytime temperature fluctuations in Suralaga being notably more extreme. These environmental conditions accelerate thermal and photo-degradation processes in polyethylene (PE) mulch, as evidenced by the thermal conductivity data in Table 6, where the highest value was recorded for the Lombok sample ($0.14015\text{ W/m}\cdot\text{K}$), followed by Bogor ($0.13867\text{ W/m}\cdot\text{K}$), and the control ($0.11962\text{ W/m}\cdot\text{K}$).

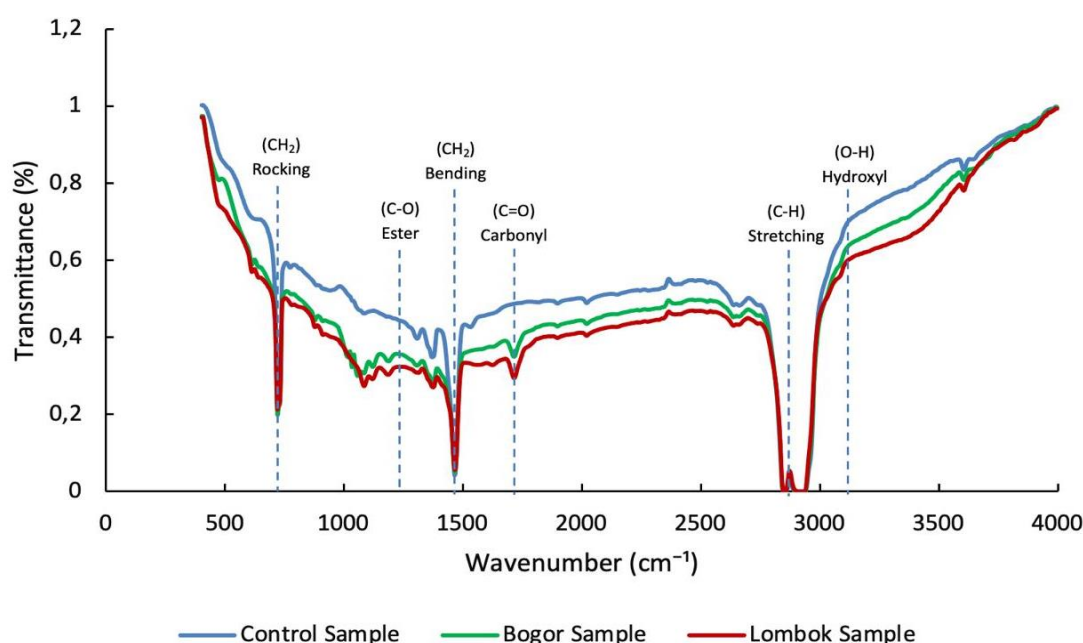


Figure 2. Comparison of FTIR spectra mulch samples

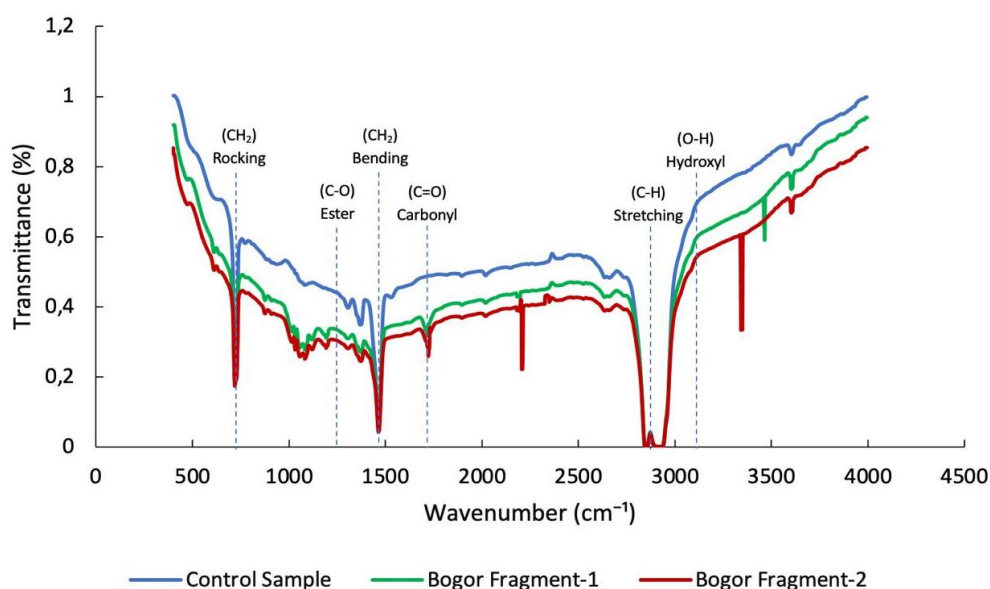


Figure 3. Comparison of FTIR spectra of Bogor fragments

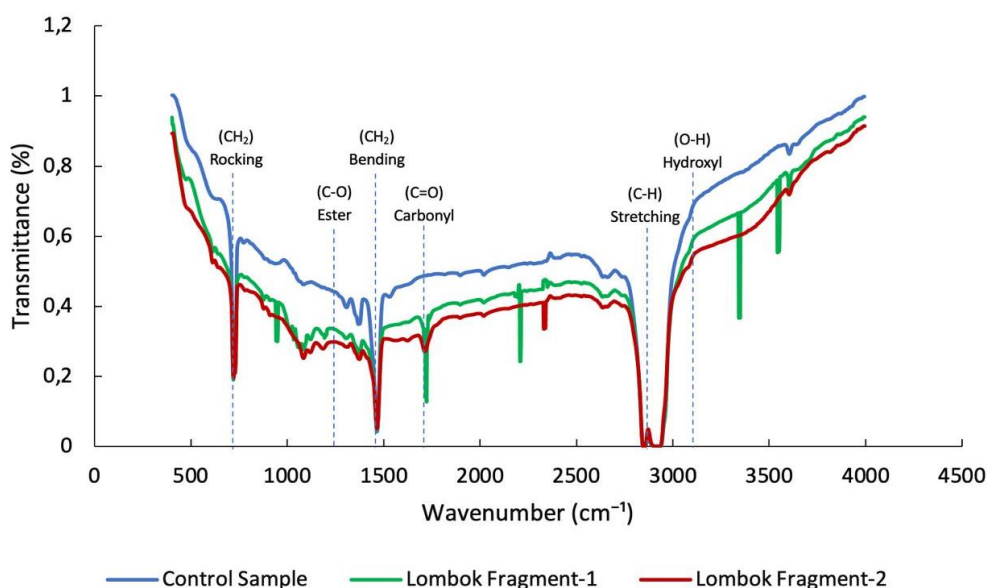


Figure 4. Comparison of FTIR spectra of Lombok fragments

Table 6. The average thermal conductivity values of the mulch samples

Sample	Average k ($\text{W m}^{-1}\text{K}^{-1}$)	Standard Deviation
Control	0.11962	± 0.0025
Bogor	0.13867	± 0.0031
Lombok	0.14015	± 0.0042

Remarks: Higher thermal conductivity in Bogor and Lombok indicates mulch degradation, with Lombok's highest value suggesting accelerated breakdown due to heat and UV exposure.

The increase in thermal conductivity is strongly correlated with polymer structural changes resulting from chain scission, microcrack formation, and increased porosity induced by prolonged exposure to high temperatures and UV radiation (Guo et al., 2023; W. Zhang et al., 2023). These alterations facilitate easier heat transfer through the mulch, thereby diminishing its effectiveness in maintaining soil temperature stability. Exposure to UV radiation and elevated temperatures accelerates the oxidation and fragmentation of polyethylene,

thereby enhancing thermal conductivity and compromising the mulch's insulating function in agricultural settings (Wei et al., 2024). UV-B exposure and thermal stress not only promote polymer chain scission but also contribute to increased porosity and microcracking, thereby enhancing the rate of heat transfer through the material (Miao et al., 2024).

The practical implication of this increase in thermal conductivity is a reduction in the mulch's capacity to regulate soil temperature, especially under hot field conditions such as those in Lombok. This can lead to greater soil temperature fluctuations, which may negatively affect plant growth and reduce agricultural productivity (Chen et al., 2025; Fernández, 2023). The primary drivers of increased thermal conductivity are photodegradation and thermal oxidation, both of which lead to polymer chain scission, microcrack development, and changes in material density (Fan et al., 2023). Oxidative processes also generate carbonyl and hydroxyl functional groups that alter the thermal behavior of the plastic (Miao et al., 2024).

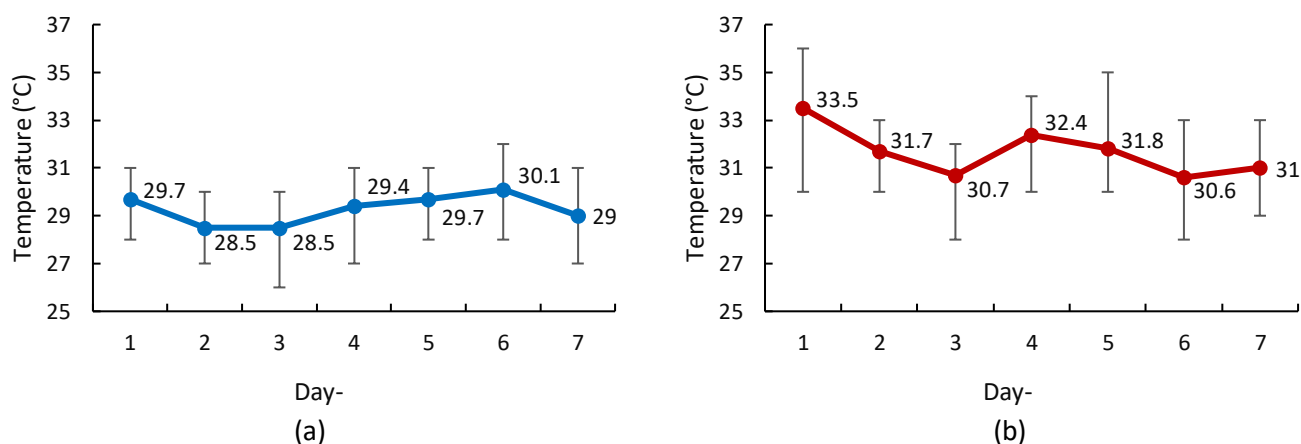


Figure 5. Comparison of average daily temperature (a) Bogor and (b) Lombok

Therefore, integrating average daily temperature data with thermal test results underscores that regions with elevated temperatures and intense UV exposure accelerate the degradation of plastic mulch (Kim et al., 2021). These findings underscore the importance of considering climatic factors when selecting mulch materials with enhanced resistance to degradation. To support sustainable agriculture, the development of alternative mulch materials—such as those based on bioplastics or other thermally and photochemically stable compounds—is essential (Wang et al., 2023).

3.4. UV-Vis analysis

Optical properties were analyzed using UV-Vis spectroscopy to evaluate the degradation level of plastic mulch based on changes in absorbance across the ultraviolet (UV) to visible light spectrum, as shown in Figure 6. Based on the UV-Vis spectral measurements, the plastic mulch samples from Lombok exhibited a significant decrease in absorbance

within the UV region (200–400 nm) compared to both the control samples and those from Bogor. This indicates the degradation of UV-stabilizing additives commonly added to polyethylene (PE) plastics, such as benzophenones and hindered amine light stabilizers (HALS), which function to reduce photo-oxidative damage from sunlight (Belhachemi et al., 2022). According to the UV-Vis absorbance data presented in Table 7, the control sample showed the highest absorbance across all wavelengths, peaking at 4.5 at 650 nm. The Bogor sample exhibited lower but still significant absorbance values, ranging from 4.0 (200 nm) to 2.3 (650 nm). In contrast, the Lombok sample showed notably low absorbance, with only 0.4 at 200 nm and a steep decline to 0.01 at 650 nm.

Based on this absorbance data and an extract solution concentration of $0.0107 \text{ mol L}^{-1}$, the molar absorptivity coefficient (ϵ) was calculated using the Beer-Lambert law. The calculated molar absorptivity values are presented in Table 8. The highest molar absorptivity coefficient in the control sample was observed at 650 nm, with a value of $420.6 \text{ L mol}^{-1}\text{cm}^{-1}$, while the Bogor and Lombok samples reached only $214.9 \text{ L mol}^{-1}\text{cm}^{-1}$ and $0.9 \text{ L mol}^{-1}\text{cm}^{-1}$, respectively. A similar pattern was observed at other wavelengths, where ϵ values were consistently highest in the control sample, followed by the Bogor sample, and lowest in the Lombok sample. This indicates that the concentration of UV-Vis active compounds in the Lombok sample was substantially lower compared to the Bogor and control samples (Wang et al., 2019). The significant differences in ϵ values among the three samples can be interpreted as evidence of varying levels of PE polymer compound degradation or presence within each soil sample (Ryu et al., 2025). Lower ϵ values correspond to a lower concentration of photo-degraded active compounds in the respective samples (Du et al., 2024).

The intense solar exposure in Lombok also contributed to increased surface porosity and fragmentation of the mulch, which in turn enhanced the material's transparency by allowing light to more easily penetrate the fragmented plastic layers (Carstensen et al., 2022; Du et al., 2024). These changes not only reduce the mulch's capacity to reflect or absorb UV radiation but also increase soil temperature due to the higher transmission of energy (Z. Zhang et al., 2025). Previous studies have shown that changes in optical properties are directly correlated with increased thermal conductivity, implying that optical degradation has direct implications for the thermal efficiency of the material (Ebert & Vidi, 2024).

Table 7. Absorbance data from UV-Vis spectrum

Wavelength (nm)	Control Sample (au)	Bogor Sample (au)	Lombok Sample (au)
200	4.2	4.0	0.4
250	2.2	2.0	0.3
300	2.1	1.9	0.2
350	2.3	2.0	0.15
400	2.7	2.3	0.1
500	3.3	2.3	0.05
600	4.0	2.3	0.02
650	4.5	2.3	0.01

Table 8. Molar absorptivity coefficient values (ϵ)

Wavelength (nm)	Control Sample ($\text{L/mol}\cdot\text{cm}$)	Bogor Sample ($\text{L/mol}\cdot\text{cm}$)	Lombok Sample ($\text{L/mol}\cdot\text{cm}$)
200	392.5	373.8	37.4
250	205.6	186.9	28.0
300	196.3	177.6	18.7
350	214.9	186.9	14.0
400	252.3	214.9	9.3
500	308.5	214.9	4.7
600	373.8	214.9	1.9
650	420.6	214.9	0.9

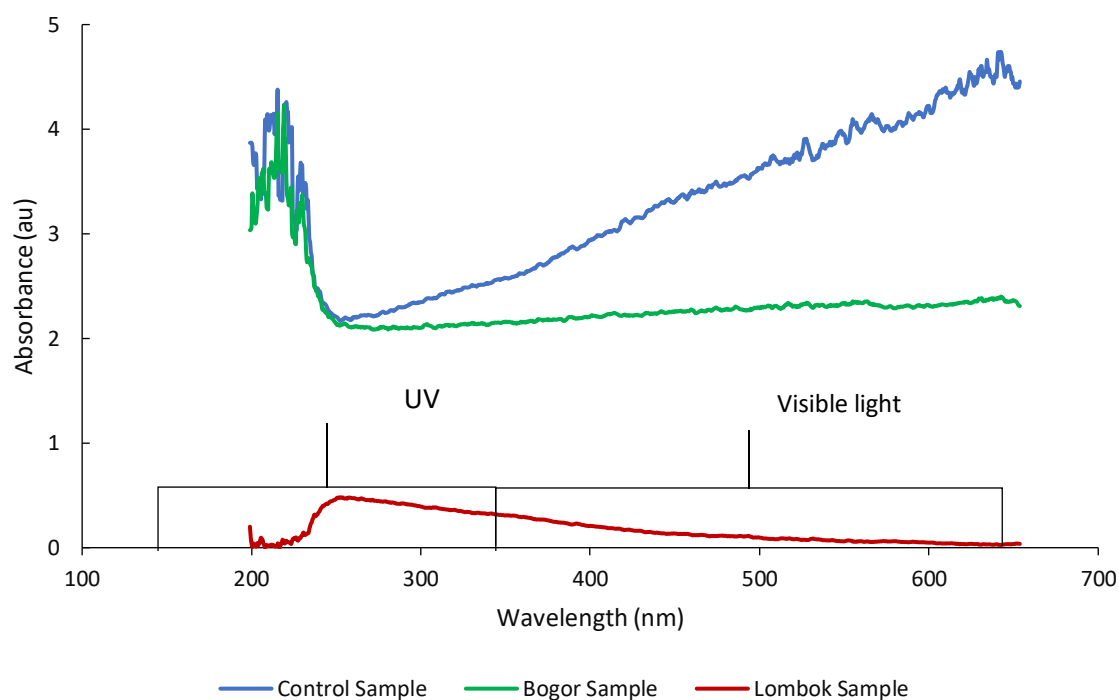


Figure 6. Comparison of UV-Vis spectra of mulch samples

The reduction in absorbance negatively impacts the plastic's ability to protect soil from thermal stress. UV-degraded plastics exhibit diminished sunlight shielding capacity, which directly affects soil structural stability, moisture retention, and microbial activity (Belhachemi et al., 2022). In this context, optical degradation is not merely an indicator of material breakdown but also has broader implications for the ecological effectiveness of plastic mulch use.

3.5. SEM analysis

Morphological structure analysis was conducted using Scanning Electron Microscopy (SEM) to evaluate the physical alterations on the surface of plastic mulch after three months of field use in two distinct locations: Cikabayan Agricultural Field, Bogor, and Suralaga, East Lombok. This technique is crucial for visualizing micro- to nanoscale surface damage on plastics, which is otherwise invisible to the naked eye. The secondary electron (SE) mode provides a detailed visualization of surface topography and morphological changes due to physical degradation, while the backscattered electron (BSE) mode offers insight into compositional dynamics during the degradation process (Chou et al., 2022). Observations in Figure 7 reveal significant structural degradation of plastic mulch influenced by a combination of temperature, humidity, and UV radiation exposure.

In the control sample, the mulch surface appeared smooth and homogeneous, with no visible cracks or large pores, indicating the polyethylene (PE) polymer structure remained intact. In contrast, the Bogor sample exhibited early-stage damage, including microcracks and slight surface erosion (Miao et al., 2024). This is likely a result of hydrothermal degradation driven by high humidity and moderate temperatures, which may accelerate mild oxidative reactions and promote microbial activity. Soil microbes capable of producing oxidative enzymes, such as peroxidases

and laccases, can contribute to the cleavage of the carbon backbone in polymers (Gkoutselis et al., 2021).

More severely, the sample from Lombok demonstrated extensive structural damage, including deep cracking, surface fragmentation, and increased porosity. These features indicate advanced photodegradation induced by intense exposure to UV-B and UV-C radiation and elevated temperatures that subject the plastic to thermal stress (Okubo et al., 2025). These conditions facilitate polymer chain scission, morphologically evident as porous, fragmented structures, which accelerate the release of microplastics into the surrounding environment. Continuous UV exposure leads to an increase in the number and depth of surface cracks due to the reduction in the material's viscoelasticity (Du et al., 2024).

Damaged morphological structures also have direct implications for the increased specific surface area of degraded plastics. This not only accelerates subsequent chemical reactions (e.g., oxidation or pollutant adsorption) but also facilitates microbial colonization and the attachment of other particles, such as heavy metals and pesticides (Wang et al., 2023). In an agricultural context, such conditions may elevate the toxicological risks to soil ecosystems and increase the potential for pollutant migration into crops (Fan et al., 2023).

Structural degradation also strongly correlates with findings from UV-Vis and FTIR analyses. Cracked and porous surfaces reduce the mulch's UV absorption capacity (as confirmed by declining absorbance values) and exhibit new functional groups such as carbonyl and hydroxyl, indicative of chemical bond scission (X. Wang et al., 2025). Furthermore, deep cracks and porous morphology contribute to increased thermal conductivity, reducing the mulch's effectiveness in regulating soil temperature (Ebert & Vidi, 2024). Thus, morphological structure analysis not only describes physical damage but also serves as a critical indicator of concurrent chemical and optical degradation processes.

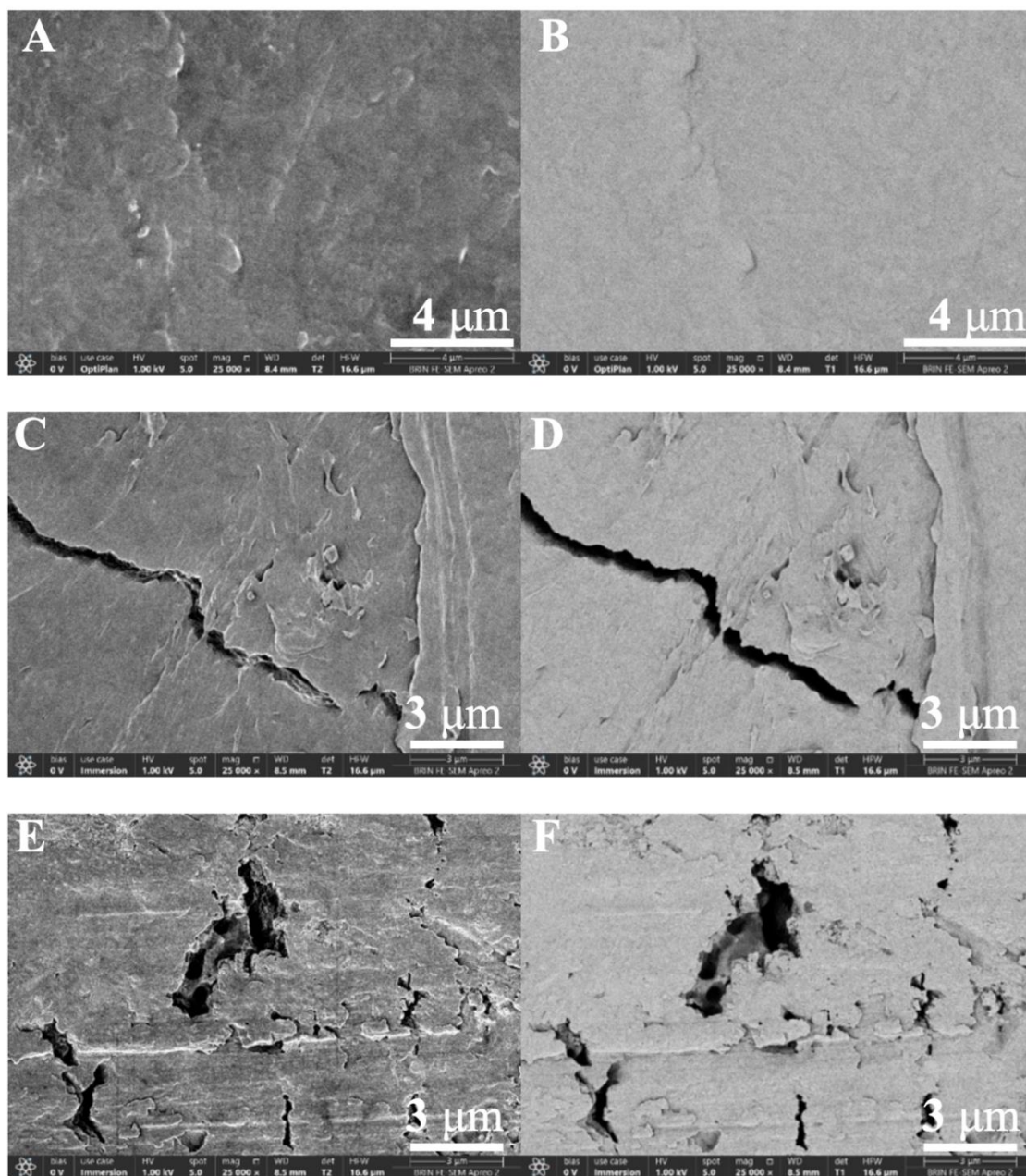


Figure 7. SEM imaging with 25,000× magnification on mulch samples: (a) control (SE), (b) control (BSE), (c) Bogor (SE), (d) Bogor (BSE), (e) Lombok (SE), (f) Lombok (BSE)

4. DISCUSSION

The findings of this study demonstrate that plastic mulch degradation significantly contributes to microplastic contamination in agricultural soils, particularly under high-temperature and UV-exposed environments such as Lombok. The analytical results from FTIR, SEM, UV-Vis, and thermal conductivity measurements provide comprehensive evidence of how environmental conditions influence polyethylene mulch degradation and subsequent microplastic formation (Rodriguez et al., 2025; Zhang et al., 2020). The degradation of polyethylene mulch is primarily driven by thermal oxidation and photodegradation, where high temperatures promote oxidation processes that generate free radicals, leading to polymer chain scission and structural weakening (Du et al., 2024). This process is further accelerated by UV radiation, which provides sufficient energy to break chemical bonds within the polymer matrix, resulting in bond cleavage

and the formation of reactive species (Cunsolo et al., 2021; Wang et al., 2023).

The FTIR analysis revealed a significantly higher intensity of oxidation-related functional groups (C=O, O-H, C-O) in Lombok samples, indicating advanced oxidative degradation due to prolonged UV exposure and elevated temperatures. This finding aligns with previous studies showing increased carbonyl index in polyethylene mulch exposed to high UV radiation (Belhachemi et al., 2022). Moreover, the increased thermal conductivity observed in Lombok samples compared to Bogor suggests significant structural damage resulting from polymer chain scission, microcrack formation, and increased porosity (Ebert & Vidi, 2024). As polymers degrade, their thermal conductivity increases due to enhanced heat transfer through cracks and voids, which is consistent with studies reporting higher thermal conductivity in degraded plastic materials (Kim et al., 2021).

The SEM analysis further confirms this structural damage, with Lombok samples exhibiting extensive fragmentation, deep cracks, and increased porosity, which contribute to higher microplastic concentrations detected in soil (440 particles kg⁻¹ compared to 240 particles kg⁻¹ in Bogor) (Fan et al., 2023). Additionally, the UV-Vis spectroscopy results showed a significant reduction in UV absorbance for Lombok samples, indicating the breakdown of UV stabilizers and increased polymer fragmentation (Wang et al., 2019). Polyethylene is particularly vulnerable to UV-induced degradation, and previous studies have reported that prolonged UV exposure accelerates material degradation through the formation of free radicals and chain scission, resulting in a loss of mechanical properties and the formation of microplastics (Carstensen et al., 2022; Du et al., 2024).

The findings of this study strongly indicate that tropical climates are particularly vulnerable to plastic mulch degradation due to the combined effects of heat, UV radiation, and mechanical stress (Rahim et al., 2022). While temperature and ultraviolet (UV) radiation are the primary abiotic drivers accelerating the degradation of polyethylene mulch, several other factors can also contribute significantly to the degradation process (Mitu et al., 2025; Samphire et al., 2023). One such factor is microbial activity. Soil microorganisms, particularly bacteria and fungi, can colonize plastic surfaces and produce enzymes that initiate the biodegradation process. These microbial processes often act synergistically with photodegradation and thermo-oxidative mechanisms, weakening polymer chains and facilitating the formation of microplastics (Wang et al., 2021).

Previous studies have demonstrated that microbial biofilms can promote the surface pitting and embrittlement of plastic materials, especially in moist and biologically active soils such as those found in tropical environments (Rahim et al., 2022). Although this study did not include direct microbiological analysis, the environmental conditions in both study sites—particularly the high microbial activity in Bogor—likely contributed to the observed degradation features, as supported by the increased surface roughness and microcracking seen in SEM images (Doğan, 2021).

The comparative analysis between the two study sites revealed that climatic differences alone do not fully explain the variation in mulch degradation and microplastic formation (Ebert & Vidi, 2024; Stachowiak et al., 2022). While Lombok exhibited more intense thermal and photodegradation—as indicated by higher thermal conductivity, stronger oxidation peaks (C=O, O-H), and greater morphological damage—Bogor showed moderate but still evident degradation features. This suggests that other factors, such as microbial activity, soil chemistry, and farming intensity, may also influence degradation rates. Additionally, differences in agricultural practices, such as irrigation frequency, tillage, and fertilizer application, may alter the micro-environment surrounding the mulch and thus affect degradation. For example, the higher moisture levels and dense microbial communities in Bogor may promote bio-fragmentation, whereas the dry, sun-exposed conditions in Lombok favor photodegradation and thermal stress. These interacting variables underscore the need for multifactorial studies that incorporate environmental, biological, and

management aspects in assessing plastic degradation dynamics.

Despite providing valuable insights, this study has several limitations. A three-month observation period may not be sufficient to fully assess the long-term degradation of plastic mulch and its cumulative effects on soil properties and microbial communities. Moreover, the study only analyzed polyethylene mulch without considering potential interactions with other pollutants commonly present in agricultural soils, such as heavy metals and pesticides. Future research should focus on conducting long-term studies to evaluate the persistence and effects of microplastics in agricultural soils, developing and testing biodegradable mulch materials that minimize environmental harm, investigating the combined effects of microplastics and other soil contaminants on soil health and crop productivity, and exploring improved manufacturing processes for plastic mulch films to enhance durability and UV resistance.

5. CONCLUSION

This study demonstrates that the degradation of plastic mulch leads to significant microplastic contamination, particularly in high-temperature and UV-exposed environments. The findings emphasize the need for sustainable alternatives to mitigate microplastic pollution in agricultural soils. Future research should focus on evaluating the long-term impact of microplastic contamination on soil fertility, microbial health, and plant growth. Developing biodegradable mulch materials that can effectively replace polyethylene while minimizing environmental harm is essential. Furthermore, prioritizing proper waste management practices and recycling initiatives is essential to mitigate the adverse effects of plastic mulch degradation. The findings of this study offer valuable insights for policymakers, researchers, and farmers in developing effective strategies to promote more sustainable agricultural practices.

Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

References

- Abbate, C., Scavo, A., Pesce, G. R., Fontanazza, S., Restuccia, A., & Mauromicale, G. (2023). Soil Bioplastic Mulches for Agroecosystem Sustainability: A Comprehensive Review. *Agriculture*, 13(1), 197. <https://doi.org/10.3390/agriculture13010197>.
- Baharuddin, A., Asran, A., Ikhtiar, M., & Suhermi. (2023). Spatial Analysis of Microplastics Using the FT-IR (Fourier Transform Infrared) Method in Green Mussel Farmers' Feces. *Window of Health : Jurnal Kesehatan*, 331-343. <https://jurnal.fkmumi.ac.id/index.php/woh/article/view/1108>.
- Bai, R., Li, Z., Liu, Q., Liu, Q., Cui, J., & He, W. (2024). The reciprocity principle in mulch film deterioration and microplastic generation. *Environmental Science: Processes & Impacts*, 26(1), 8-15. <https://doi.org/10.1039/D3EM00402C>.

- Belhachemi, A., Maatoug, M. h., & Canela-Garayoa, R. (2022). Comparative analysis by UV-vis and FT-IR spectroscopy of the chemical degradation of polyethylene used as greenhouse cover film. *Journal of Elastomers & Plastics*, 54(6), 891-905. <https://doi.org/10.1177/00952443221077439>.
- Bo, L., Guan, H., & Mao, X. (2023). Diagnosing crop water status based on canopy temperature as a function of film mulching and deficit irrigation. *Field Crops Research*, 304, 109154. <https://doi.org/10.1016/j.fcr.2023.109154>.
- Broda, J., Gawłowski, A., Rom, M., Kukulski, T., & Kobiela-Mendrek, K. (2024). Thermoregulation and Soil Moisture Management in Strawberry Cultivation Mulched with Sheep Wool. *Applied Sciences*, 14(23), 10884. <https://doi.org/10.3390/app142310884>.
- Carstensen, L., Beil, S., Börnick, H., & Stolte, S. (2022). Structure-related endocrine-disrupting potential of environmental transformation products of benzophenone-type UV filters: A review. *Journal of Hazardous Materials*, 430, 128495. <https://doi.org/10.1016/j.jhazmat.2022.128495>.
- Chen, C., Huang, H., Abdalkarim, S. Y. H., Asad, R. A. M., & Yu, H.-Y. (2025). Establishing a predictive model for ultraviolet degradation to rapidly estimate the service life of poly (lactic acid)-based mulch film for agricultural protection. *Journal of Cleaner Production*, 508, 145587. <https://doi.org/10.1016/j.jclepro.2025.145587>.
- Chong, C. S., Ishak, I., Mahat, R. H., & Amin, Y. M. (1997). UV-VIS and FTIR spectral studies of CR-39 plastics irradiated with X-rays. *Radiation Measurements*, 28(1), 119-122. [https://doi.org/10.1016/S1350-4487\(97\)00051-6](https://doi.org/10.1016/S1350-4487(97)00051-6).
- Chou, S.-H., Chuang, Y.-K., Lee, C.-M., Chang, Y.-S., Jhang, Y.-J., Yeh, C.-W., . . . Hsiao, I. L. (2022). Visualization and (Semi-)quantification of submicrometer plastics through scanning electron microscopy and time-of-flight secondary ion mass spectrometry. *Environmental Pollution*, 300, 118964. <https://doi.org/10.1016/j.envpol.2022.118964>.
- Cunsolo, S., Williams, J., Hale, M., Read, D. S., & Couceiro, F. (2021). Optimising sample preparation for FTIR-based microplastic analysis in wastewater and sludge samples: multiple digestions. *Analytical and Bioanalytical Chemistry*, 413(14), 3789-3799. <https://doi.org/10.1007/s00216-021-03331-6>.
- Doğan, M. (2021). Ultraviolet light accelerates the degradation of polyethylene plastics. *Microscopy Research and Technique*, 84(11), 2774-2783. <https://doi.org/10.1002/jemt.23838>.
- Dong, Y., Ren, L., Jia, X., Liao, X., Huang, L., Zhang, X., . . . Xu, L. (2025). Microplastics decrease soil compressibility but have no major impact on soil physical properties. *Soil and Tillage Research*, 253, 106688. <https://doi.org/10.1016/j.still.2025.106688>.
- Du, B., Lee, C., & Ji, Y. (2024). Study of Factors Affecting UV-Induced Photo-Degradation in Different Types of Polyethylene Sheets. *Polymers*, 16(19), 2709. <https://doi.org/10.3390/polym16192709>.
- Ebert, H.-P., & Vidi, S. (2024). Correct Use of the Guarded-Hot-Plate Method for Thermal Conductivity Measurements on Solids. *International Journal of Thermophysics*, 45(2), 20. <https://doi.org/10.1007/s10765-023-03307-x>.
- En-Nejmy, K., El Fels, L., El Hayany, B., & Hafidi, M. (2025). Microplastics behavior and distribution in mulched agricultural soil under semi-arid climate: A case study from Morocco. *Pedosphere*. <https://doi.org/10.1016/j.pedsph.2025.05.003>.
- Fajri, N., Cahya, E. P., Riandi, & Sriyati, S. (2024). Validasi Metode Analisis Konsentrasi Larutan Kopi berdasarkan Spektroskopi Absorpsi Cahaya. *JIPFRI (Jurnal Inovasi Pendidikan Fisika dan Riset Ilmiah)*, 8(1), 51-59. <https://doi.org/10.30599/jipfri.v8i1.2101>.
- Fan, D., Jia, G., Wang, Y., & Yu, X. (2023). The effectiveness of mulching practices on water erosion control: A global meta-analysis. *Geoderma*, 438, 116643. <https://doi.org/10.1016/j.geoderma.2023.116643>.
- Fernández, C. (2023). Effects of post-fire application of straw mulch strips on soil erosion, soil moisture and vegetation regeneration in European dry heathlands in NW Spain. *Ecological Engineering*, 196, 107095. <https://doi.org/10.1016/j.ecoleng.2023.107095>.
- Gkoutselis, G., Rohrbach, S., Harjes, J., Obst, M., Brachmann, A., Horn, M. A., & Rambold, G. (2021). Microplastics accumulate fungal pathogens in terrestrial ecosystems. *Scientific Reports*, 11(1), 13214. <https://doi.org/10.1038/s41598-021-92405-7>.
- Guo, K., Cao, M., Gu, F., Wu, F., Yang, H., Xu, H., & Hu, Z. (2023). Mechanical Properties of Metallocene Linear Low-Density Polyethylene Mulch Films Correlate with Ultraviolet Irradiation and Film Thickness. *Sustainability*, 15(8), 6713. <https://doi.org/10.3390/su15086713>.
- Hou, L., Xi, J., Chen, X., Li, X., Ma, W., Lu, J., . . . Lin, Y. B. (2019). Biodegradability and ecological impacts of polyethylene-based mulching film at agricultural environment. *Journal of Hazardous Materials*, 378, 120774. <https://doi.org/10.1016/j.jhazmat.2019.120774>.
- Hudson, T. B., Alford, A. M., Bilbo, T. R., Boyle, S. C., Doughty, H. B., Kuhar, T. P., . . . Blubaugh, C. K. (2023). Living mulches reduce natural enemies when combined with frequent pesticide applications. *Agriculture, Ecosystems & Environment*, 357, 108680. <https://doi.org/10.1016/j.agee.2023.108680>.
- Jemec Kokalj, A., Dolar, A., Nagode, A., Drobne, D., Kuljanin, A., & Kalčíková, G. (2024). Response of terrestrial crustacean Porcellio scaber and mealworm Tenebrio molitor to non-degradable and biodegradable fossil-based mulching film microplastics. *Science of The Total Environment*, 951, 175379. <https://doi.org/10.1016/j.scitotenv.2024.175379>.
- Ju, T., Yang, K., Ji, D., Chang, L., Alquiza, M. d. J. P., & Li, Y. (2025). Microplastics influence nutrient content and quality of salt-affected agricultural soil under plastic

- mulch. *Environmental Research*, 264, 120376. <https://doi.org/10.1016/j.envres.2024.120376>.
- Junga, R., Wzorek, M., Sobek, S., Sajdak, M., & Yilmaz, E. (2024). Co-pyrolysis of animal manure and plastic waste study using TG-FTIR analysis. *Journal of Analytical and Applied Pyrolysis*, 181, 106598. <https://doi.org/10.1016/j.jaap.2024.106598>.
- Kim, D., Lee, S., & Yang, I. (2021). Verification of thermal conductivity measurements using guarded hot plate and heat flow meter methods. *Journal of the Korean Physical Society*, 78(12), 1196-1202. <https://doi.org/10.1007/s40042-021-00177-0>.
- Klempová, S., Oravec, M., & Vizárová, K. (2023). Analysis of thermally and UV-Vis aged plasticized PVC using UV-Vis, ATR-FTIR and Raman spectroscopy. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 294, 122541. <https://doi.org/10.1016/j.saa.2023.122541>.
- Kumar, R., Sharma, S., Pathak, D., Dhiman, N., & Arora, N. (2017). Ionic conductivity, FTIR and thermal studies of nano-composite plasticized proton conducting polymer electrolytes. *Solid State Ionics*, 305, 57-62. <https://doi.org/10.1016/j.ssi.2017.04.020>.
- Maiket, Y., Yeetsorn, R., Surathin, N., Jirawutthiwongchai, J., & Boonyarattanakalin, S. (2025). The role of TPS in promoting the disintegration of LDPE/TPS blends to unravel the degradation mechanism of plastic films. *Journal of Hazardous Materials*, 488, 137400. <https://doi.org/10.1016/j.jhazmat.2025.137400>.
- Mansoor, Z., Tchenbou-Magaia, F., Kowalczyk, M., Adamus, G., Manning, G., Parati, M., . . . Khan, H. (2022). Polymers Use as Mulch Films in Agriculture—A Review of History, Problems and Current Trends. *Polymers*, 14(23), 5062. <https://doi.org/10.3390/polym14235062>.
- Marczak-Grzesik, M., Tarach, K. A., Olszewska, A., Sobańska, K., Kowalczyk, A., & Góra-Marek, K. (2025). UV-vis methodology for evaluation of adsorption of polystyrene nanoplastics by zeolite adsorbents: A case of carboxylate-modified polystyrene. *Journal of Environmental Chemical Engineering*, 13(4), 117306. <https://doi.org/10.1016/j.jece.2025.117306>.
- Mecozzi, M., Pietroletti, M., & Monakhova, Y. B. (2016). FTIR spectroscopy supported by statistical techniques for the structural characterization of plastic debris in the marine environment: Application to monitoring studies. *Marine Pollution Bulletin*, 106(1), 155-161. <https://doi.org/10.1016/j.marpolbul.2016.03.012>.
- Merino, D., Gutiérrez, T. J., & Alvarez, V. A. (2019). Structural and Thermal Properties of Agricultural Mulch Films Based on Native and Oxidized Corn Starch Nanocomposites. *Starch - Stärke*, 71(7-8), 1800341. <https://doi.org/10.1002/star.201800341>.
- Merino, D., Zych, A., & Athanassiou, A. (2022). Biodegradable and Biobased Mulch Films: Highly Stretchable PLA Composites with Different Industrial Vegetable Waste. *ACS Applied Materials & Interfaces*, 14(41), 46920-46931. <https://doi.org/10.1021/acsami.2c10965>.
- Miao, H., Zhang, S., Gao, W., Zhou, J., Cai, H., Wu, L., . . . Liu, T. (2024). Microplastics occurrence and distribution characteristics in mulched agricultural soils of Guizhou province. *Scientific Reports*, 14(1), 21505. <https://doi.org/10.1038/s41598-024-72829-7>.
- Miao, J., Huang, W., Pan, R., & Zhou, K. (2023). Research progress and hotspot analysis of soil microplastics: a bibliometrics-based review [Review]. *Frontiers in Environmental Science*, Volume 11 - 2023. <https://doi.org/10.3389/fenvs.2023.1297646>.
- Mitu, F. A., Ashraful, M., Kader, M. A., Talukder, F. U., Akter, T., Akter, N., . . . Singha, A. (2025). Preserving soil properties and enhancing cauliflower yield with black plastic mulch in Bangladesh. *Sains Tanah Journal of Soil Science and Agroclimatology*, 21(2), 8. <https://doi.org/10.20961/stjssa.v21i2.89262>.
- Narloch, I., Gackowska, A., & Wejnerowska, G. (2022). Microplastic in the Baltic Sea: A review of distribution processes, sources, analysis methods and regulatory policies. *Environmental Pollution*, 315, 120453. <https://doi.org/10.1016/j.envpol.2022.120453>.
- Nguyen, M.-K., Rakib, M. R. J., Hwangbo, M., & Kim, J. (2025). Microplastic accumulation in soils: Unlocking the mechanism and biodegradation pathway. *Journal of Hazardous Materials Advances*, 17, 100629. <https://doi.org/10.1016/j.hazadv.2025.100629>.
- Noor-ul-Ain, Aslam, A., & Haider, F. U. (2022). Effects of Mulching on Soil Biota and Biological Indicators of Soil Quality. In K. Akhtar, M. Arif, M. Riaz, & H. Wang (Eds.), *Mulching in Agroecosystems: Plants, Soil & Environment* (pp. 15-40). Springer Nature Singapore. https://doi.org/10.1007/978-981-19-6410-7_2.
- Nugraha, F., Kurniawan, H., & Yastiara, I. (2023). Penetapan Kadar Paracetamol dalam Jamu di Kota Pontianak Menggunakan Instrumen Spektrofotometri UV-Vis. *Indonesian Journal of Pharmaceutical Education*, 3(1), 77-87. <https://doi.org/10.37311/ijpe.v3i1.18876>.
- Okubo, K., Manago, G., Tanabe, T., Yu, J., Liu, X., & Sasaki, T. (2025). Identifying plastic materials in post-consumer food containers and packaging waste using terahertz spectroscopy and machine learning. *Waste Management*, 196, 32-41. <https://doi.org/10.1016/j.wasman.2025.02.018>.
- Olesen, K. B., van Alst, N., Simon, M., Vianello, A., Liu, F., & Vollertsen, J. (2017). Analysis of Microplastics using FTIR Imaging. *Agilent Application Note Environment*. https://www.agilent.com/cs/library/applications/5991-8271EN_microplastics_ftir_application.pdf.
- Pahlawan, M. F. R., Kim, Y., Aline, U., Zahroh, A., Masithoh, R. E., Kim, M. S., . . . Cho, B.-K. (2025). Non-destructive identification of microplastics in soil using spectroscopy and hyperspectral imaging. *TrAC Trends in Analytical Chemistry*, 187, 118216. <https://doi.org/10.1016/j.trac.2025.118216>.
- Peksen, A., Ates, U., Ic, S., & Ozturk, B. (2023). Impact of Biodegradable Mulches on Qualitative Characteristics and Bioactive Compounds of Capia Pepper (*Capsicum Annum* L.) Under Cold Storage. *Journal of Soil Science*

- and *Plant Nutrition*, 23(3), 4412-4425. <https://doi.org/10.1007/s42729-023-01359-4>.
- Qiang, L., Hu, H., Li, G., Xu, J., Cheng, J., Wang, J., & Zhang, R. (2023). Plastic mulching, and occurrence, incorporation, degradation, and impacts of polyethylene microplastics in agroecosystems. *Ecotoxicology and Environmental Safety*, 263, 115274. <https://doi.org/10.1016/j.ecoenv.2023.115274>.
- Rahim, H. U., Akbar, W. A., Begum, N., Uddin, M., Qaswar, M., & Khan, N. (2022). Mulches and Microplastic Pollution in the Agroecosystem. In K. Akhtar, M. Arif, M. Riaz, & H. Wang (Eds.), *Mulching in Agroecosystems: Plants, Soil & Environment* (pp. 315-328). Springer Nature Singapore. https://doi.org/10.1007/978-981-19-6410-7_18
- Rodriguez, N., Xing, F., Gillor, O., Guvendiren, M., & Axe, L. (2025). Methodology development: evaluation of structural, thermal, and mechanical properties of poly(lactic acid)/poly(butylene adipate-co-terephthalate) blends for biodegradable mulch. *Polymer Bulletin*, 82(9), 3685-3713. <https://doi.org/10.1007/s00289-025-05681-y>.
- Romano, I., Ventrino, V., Schettino, M., Magaraci, G., & Pepe, O. (2024). Changes in Soil Microbial Communities Induced by Biodegradable and Polyethylene Mulch Residues Under Three Different Temperatures. *Microbial Ecology*, 87(1), 101. <https://doi.org/10.1007/s00248-024-02420-0>.
- Ryu, Y., Bouharras, F. E., Cha, M., Mudondo, J., Kim, Y., Ramakrishnan, S. R., . . . Kim, H. T. (2025). Recent advancements in the evolution, production, and degradation of biodegradable mulch films: A review. *Environmental Research*, 277, 121629. <https://doi.org/10.1016/j.envres.2025.121629>.
- Salama, K., & Geyer, M. (2023). Plastic Mulch Films in Agriculture: Their Use, Environmental Problems, Recycling and Alternatives. *Environments*, 10(10), 179. <https://doi.org/10.3390/environments10100179>.
- Samphire, M., Chadwick, D. R., & Jones, D. L. (2023). Biodegradable plastic mulch films increase yield and promote nitrogen use efficiency in organic horticulture. *Frontiers in Agronomy*, Volume 5 - 2023. <https://doi.org/10.3389/fagro.2023.1141608>.
- Sandt, C., Waeytens, J., Deniset-Besseau, A., Nielsen-Leroux, C., & Réjasse, A. (2021). Use and misuse of FTIR spectroscopy for studying the bio-oxidation of plastics. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 258, 119841. <https://doi.org/10.1016/j.saa.2021.119841>.
- Sang, T., Wallis, C. J., Hill, G., & Britovsek, G. J. P. (2020). Polyethylene terephthalate degradation under natural and accelerated weathering conditions. *European Polymer Journal*, 136, 109873. <https://doi.org/10.1016/j.eurpolymj.2020.109873>.
- Senevirathne, G. I., Gimhani, T. D. M., Reay, M. K., Perera, C., Ariyaratna, M., Karunarathna, A. K., . . . Chathurika, J. A. S. (2025). In situ degradation of three contrasting plastic mulch films under maize cultivation in tropical conditions. *Environmental Advances*, 20, 100628. <https://doi.org/10.1016/j.envadv.2025.100628>.
- Sintim, H. Y., Bary, A. I., Hayes, D. G., Wadsworth, L. C., Anunciado, M. B., English, M. E., . . . Flury, M. (2020). In situ degradation of biodegradable plastic mulch films in compost and agricultural soils. *Science of The Total Environment*, 727, 138668. <https://doi.org/10.1016/j.scitotenv.2020.138668>.
- Somanathan, H., Sathasivam, R., Sivaram, S., Mariappan Kumaresan, S., Muthuraman, M. S., & Park, S. U. (2022). An update on polyethylene and biodegradable plastic mulch films and their impact on the environment. *Chemosphere*, 307, 135839. <https://doi.org/10.1016/j.chemosphere.2022.135839>.
- Stachowiak, T., Postawa, P., Malińska, K., Drózd, D., & Pudełko, A. (2022). Comparison of Physical and Thermal Properties of Mulching Films Made of Different Polymeric Materials. *Materials*, 15(21), 7610. <https://doi.org/10.3390/ma15217610>.
- Villegas-Camacho, O., Alejo-Eleuterio, R., Francisco-Valencia, I., Granda-Gutiérrez, E., Martínez-Gallegos, S., & Illescas, J. (2024). FTIR-Plastics: A Fourier Transform Infrared Spectroscopy dataset for the six most prevalent industrial plastic polymers. *Data in Brief*, 55, 110612. <https://doi.org/10.1016/j.dib.2024.110612>.
- Wang, C., Zeng, T., Gu, C., Zhu, S., Zhang, Q., & Luo, X. (2019). Photodegradation Pathways of Typical Phthalic Acid Esters Under UV, UV/TiO₂, and UV-Vis/Bi₂WO₆ Systems. *Frontiers in Chemistry*, Volume 7 - 2019. <https://doi.org/10.3389/fchem.2019.00852>.
- Wang, T., Liu, L., Zhao, Q., Meng, Z., & Li, W. (2023). The aging of polyethylene mulch films in the presence of cadmium. *Ecotoxicology and Environmental Safety*, 266, 115569. <https://doi.org/10.1016/j.ecoenv.2023.115569>.
- Wang, T., Ma, Y., & Ji, R. (2021). Aging Processes of Polyethylene Mulch Films and Preparation of Microplastics with Environmental Characteristics. *Bulletin of Environmental Contamination and Toxicology*, 107(4), 736-740. <https://doi.org/10.1007/s00128-020-02975-x>.
- Wang, X., Ni, L., Zhang, C., Xu, Q., & Ye, S. (2025). Using a one-dimensional convolutional neural network on FTIR spectroscopy to measure the thickness of composite plastic films. *Infrared Physics & Technology*, 147, 105777. <https://doi.org/10.1016/j.infrared.2025.105777>.
- Wang, Y., Bai, R.-H., Liu, Q., Tang, Q.-X., Xie, C.-H., Richel, A., . . . He, W.-Q. (2025). Degradation of biodegradable plastic films in soil: microplastics formation and soil microbial community dynamics. *Journal of Hazardous Materials*, 492, 138250. <https://doi.org/10.1016/j.jhazmat.2025.138250>.
- Wei, H., Zhang, K., Chai, N., Wang, Y., Li, Y., Yang, J., . . . Zhang, F. (2024). Exploring low-carbon mulching strategies for maize and wheat on-farm: Spatial responses, factors and mitigation potential. *Science of The Total*

- Environment*, 906, 167441. <https://doi.org/10.1016/j.scitotenv.2023.167441>.
- Xie, Y., Abdalkarim, S. Y. H., Adil Mahjoob, H., Chen, C., Huang, H., & Yu, H.-Y. (2025). Unveiling the impact of soil depth on degradation of durable nanocomposite mulch-derived residue migration dynamics in plant ecosystems. *Journal of Hazardous Materials*, 493, 138364. <https://doi.org/10.1016/j.jhazmat.2025.138364>.
- Xie, Z., Xiong, Q., Fang, Y., Zhang, Q., Liang, W., Cheng, J., . . . Zhao, J. (2023). Novel Biodegradable Composite Mulch Film Embedded with Temperature-Responsive Pesticide Microcapsules for Durable Control of Phytophthora Root Rot on Soybean. *ACS Sustainable Chemistry & Engineering*, 11(26), 9868-9879. <https://doi.org/10.1021/acssuschemeng.3c02824>.
- Yang, C., & Gao, X. (2022). Impact of microplastics from polyethylene and biodegradable mulch films on rice (*Oryza sativa* L.). *Science of The Total Environment*, 828, 154579. <https://doi.org/10.1016/j.scitotenv.2022.154579>.
- Yang, C., Zhang, N., Zhao, F., & Wang, J. (2025). Mulching practices decreased soil microbial carbon degradation potential under spring maize in the Loess Plateau of China. *Agriculture, Ecosystems & Environment*, 381, 109465. <https://doi.org/10.1016/j.agee.2024.109465>.
- Yang, Z., Zhang, J., Haruka, N., Murat, C., & Arakawa, H. (2024). Spectral analysis of environmental microplastic polyethylene (PE) using average spectra. *Science of The Total Environment*, 927, 171871. <https://doi.org/10.1016/j.scitotenv.2024.171871>.
- Yu, H., Zhang, M., Liu, H., Xiao, J., Men, J., Cernava, T., . . . Jin, D. (2025). Comparison of plastisphere microbiomes during the degradation of conventional and biodegradable mulching films. *Journal of Hazardous Materials*, 487, 137243. <https://doi.org/10.1016/j.jhazmat.2025.137243>.
- Zhang, J., Du, L., Xing, Z., Zhang, R., Li, F., Zhong, T., . . . Liu, X. (2023). Effects of dual mulching with wheat straw and plastic film under three irrigation regimes on soil nutrients and growth of edible sunflower. *Agricultural Water Management*, 288, 108453. <https://doi.org/10.1016/j.agwat.2023.108453>.
- Zhang, J., Wang, K., Hao, T., Zhang, J., Müller, C., Florent, P., . . . Liu, X. (2025). Long-term plastic film mulching promotes microplastic accumulation and alters gross nitrogen transformation in soil. *Applied Soil Ecology*, 208, 106007. <https://doi.org/10.1016/j.apsoil.2025.106007>.
- Zhang, W., Ma, J., Cui, Z., Xu, L., Liu, Q., Li, J., . . . Zeng, X. (2023). Effects of Biodegradable Plastic Mulch Film on Cabbage Agronomic and Nutritional Quality Traits, Soil Physicochemical Properties and Microbial Communities. *Agronomy*, 13(5), 1220. <https://doi.org/10.3390/agronomy13051220>.
- Zhang, Y., Feng, R., Nie, W., Wang, F., & Feng, S. (2020). Plastic Film Mulch Performed Better in Improving Heat Conditions and Drip Irrigated Potato Growth in Northwest China than in Eastern China. *Water*, 12(10), 2906. <https://doi.org/10.3390/w12102906>.
- Zhang, Z., Fan, X., Zhang, R., Pan, X., Zhang, X., Ding, Y., & Liu, Y. (2025). Biodegradation characterization and mechanism of low-density polyethylene by the enriched mixed-culture from plastic-contaminated soil. *Journal of Hazardous Materials*, 494, 138530. <https://doi.org/10.1016/j.jhazmat.2025.138530>.