INTERNATIONAL MULTI DISCIPLINARY JOURNAL FOR RESEARCH & DEVELOPMENT
eISSN 2394-6334 Impact factor: 8.854 Volume 13, issue 05 (2026)

EFFECT OF BIODEGRADABLE MULCH FILM DECOMPOSITION RATE ON ROOT-ZONE MICROCLIMATE AND YIELD FORMATION IN CUCURBIT CROPS UNDER ARID CONDITIONS

Nigmatjonov Sardor Abdumannobovich

Doctoral Student at the Research Institute of Agricultural Mechanization

Abstract. Plastic film residues accumulating in agricultural soils represent a significant environmental challenge worldwide, driving demand for biodegradable alternatives. This three-year field study evaluated five commercially available biodegradable mulch films (polylactic acid [PLA], polyhydroxyalkanoate [PHA], thermoplastic starch [TPS], starch-polybutylene adipate terephthalate blend [PBAT], and paper-based mulch) against a conventional low-density polyethylene (LDPE) control on watermelon (Citrullus lanatus cv. 'Crimson Sweet') and cantaloupe (Cucumis melo cv. 'Topmark') plantations in Uzbekistan (40°51′N, 68°43′E). Key microclimate variables root-zone temperature at 5, 15, and 25 cm depths, volumetric soil water content (SWC), and CO_2 flux from soil surface were monitored continuously. Tensile strength degradation kinetics were modelled using a modified Avrami equation. Results showed that PBAT blend films maintained structural integrity for 85–92 days post-installation, matching the critical crop establishment period (65–70 days), while TPS films degraded prematurely within 38–42 days under field UV exposure. Root-zone temperature in PBAT plots was 2.9°C higher than in LDPE plots at 5 cm depth due to increased CO_2 flux from microbial film decomposition. Watermelon marketable yield in PBAT plots reached 41.3 t ha^{-1}, surpassing LDPE (38.6 t ha^{-1}) by 7.0%, with no statistically significant residue detected at harvest ($p = 0.08$). These findings provide quantitative design criteria degradation half-life, thickness-to-tensile-strength ratio, and UV stabilizer concentration for biodegradable mulch films optimized for arid Central Asian growing conditions.

Key words: biodegradable mulch, PBAT, PLA, degradation kinetics, root-zone temperature, cucurbits, arid agriculture, CO_2 flux, tensile strength, Avrami model.

INTRODUCTION

Global production of agricultural plastic films exceeded 7.4 million tonnes in 2022, of which mulch films accounted for approximately 42%, and more than 60% of these plastics were never formally collected after the growing season [1]. In Uzbekistan, a country with more than 3.7 million hectares of irrigated farmland, the annual consumption of polyethylene mulch film is estimated at 28,000 tonnes, leaving behind roughly 18,000 tonnes of microplastic-laden residue each year [2]. This accumulation impairs soil macroporosity, inhibits earthworm activity, and intercepts capillary water movement effects that compound over consecutive seasons.

Biodegradable mulch films promise to dissolve this residue problem by converting polymer mass to CO_2, H_2O, and microbial biomass within one to three growing seasons [3]. However, degradation rate is acutely sensitive to soil temperature, UV irradiance, and moisture parameters that fluctuate substantially in the continental arid climate of Central Asia. Premature mechanical failure before canopy closure exposes inter-row soil, negates weed suppression benefits, and can reduce crop stand by 15–22% [4]. Conversely, excessively slow degradation preserves the plastic pollution problem the technology is intended to resolve.

Despite a rich body of literature from temperate and subtropical environments [5, 6], quantitative performance data for biodegradable films under Central Asian conditions characterized by solar irradiance exceeding 700 W m^{-2}, daily temperature amplitude of 18–24°C, and cumulative annual precipitation below 250 mm are almost entirely absent. Agronomic decisions in Uzbekistan therefore rely on European or East Asian product specifications that may significantly misrepresent local behaviour.

This study addresses that gap through three specific objectives: to quantify the degradation kinetics of five commercially available biodegradable film formulations under Uzbekistan field conditions; to characterize root-zone microclimate differences among film types throughout the cropping season; and to establish film design criteria thickness, UV stabilizer level, and polymer blend ratio that ensure structural integrity throughout the critical crop establishment window while guaranteeing complete in-situ decomposition before the next planting cycle.

LITERATURE REVIEW

The development of biodegradable agricultural films has progressed through three broad generations. First-generation starch-blend films, introduced commercially in the 1990s, suffered from rapid hydrolysis and poor UV resistance, rendering them unsuitable for multi-week applications [7]. Second-generation aliphatic-aromatic copolymers such as PBAT and polybutylene succinate (PBS) demonstrated substantially improved durability and have dominated the market since approximately 2005 [8].

Sintim et al. [9] conducted a landmark four-year comparison of PBAT and LDPE mulch on processing tomato in California and reported that end-of-season soil residue in PBAT plots was 98.3% lower by mass than in LDPE plots, with no significant yield penalty. Similarly, Moreno et al. [10] showed in Spain that PLA/PHA blend films achieved mechanical performance equivalent to LDPE for 70 days before initiating visible fragmentation, matching the pepper crop establishment period precisely.

Degradation modelling has largely relied on empirical approaches. The Avrami equation, originally derived for polymer crystallisation kinetics, was adapted by Briassoulis et al. [11] to describe mulch film tensile strength loss as a function of accumulated UV dose and soil temperature integral (degree-days). Their model accurately predicted degradation onset but underestimated the terminal fragmentation phase, prompting subsequent refinements incorporating moisture content as a co-predictor [12].

Soil CO_2 flux as an indirect indicator of film decomposition rate was validated by Li et al. [13], who demonstrated a linear correlation ($R^2 = 0.87$) between cumulative CO_2 efflux and mass loss in buried PBAT coupons across a soil temperature range of 15–35°C. This relationship offers a non-destructive field monitoring approach that has not yet been tested in hyper-arid soils with low baseline organic matter (<1.1%), such as those prevalent in irrigated areas of Uzbekistan.

Root-zone heating attributable to biodegradable film decomposition distinct from the purely radiative heating effect of intact opaque films was first reported by Bandopadhyay et al. [14], who measured a transient 1.4°C soil temperature increase coinciding with peak microbial respiration during film fragmentation. This exothermic microbial activity represents a previously unquantified microclimate modification that may influence both crop phenology and pest dynamics.

MATERIALS AND METHODS

Experimental site and climate characterisation

Field trials were conducted at the Experimental Station of the Institute of Soil Science and Agrochemistry (40°51′N, 68°43′E, elevation 312 m a.s.l.) during three consecutive seasons: April-September. The soil is classified as a Calcic Kastanozem (WRB 2015) with the following physicochemical properties: clay 18.4%, silt 41.7%, sand 39.9%, bulk density 1.41 g cm^{-3}, organic matter 0.87%, pH_{20} 7.9, electrical conductivity 0.38 dS m^{-1}.

Long-term mean annual precipitation at the site is 198 mm; during trial years actual precipitation was 204 mm (2020), 176 mm (2021), and 221 mm (2022). Cumulative UV-A irradiance (315–400 nm, measured with a Kipp & Zonen CUV5 radiometer) over the April-September period averaged 1,247 kJ m^{-2} yr^{-1}—approximately 1.6× higher than the mean reported for northern Italy and 2.3× higher than Germany, reflecting the importance of local calibration for degradation models.

Film treatments and physical characterisation

Six mulch film treatments were evaluated in a randomized complete block design with four replications (plot size: 12 m × 6 m = 72 m²). Films were installed by machine on 120 cm-wide raised beds with drip irrigation tape placed beneath each film. Treatment descriptions are provided in Table 1.

Table 1. Mulch film treatments and initial physical properties

Code	Film type	Polymer	Thick-ness (µm)	Tensile str. (MPa)	UV stabiliser (ppm)	Expected lifespan (days)
LDPE	Conventional	Low-density PE	25	28.4	2,400	>365 (control)
PLA	Biobased	Polylactic acid	20	18.6	800	60–90
PHA	Biobased	Polyhydroxyalkanoate	22	21.3	600	90–120
TPS	Biobased	Thermoplastic starch	30	9.8	0	30–45
PBAT	Compostable	Starch/PBAT blend	25	24.7	1,200	80–100
PAPER	Natural	Kraft paper + wax	400 g m^{-2}	N/A	0	50–70

Degradation kinetics measurements

Tensile strength (TS) retention was measured on 25 × 100 mm coupons excised from field-installed films at 14-day intervals using a portable dynamometer (Mecmesin BFG 500N). Five replicate coupons were tested per treatment per sampling date. Degradation onset was defined as the date at which TS fell below 50% of its initial value. The modified Avrami model was fitted to normalised TS data:

$$TS(t) / TS_0 = exp[-k \cdot (t - t_0)^n]$$

where k is the degradation rate constant (day^{-1}), t_0 is the induction period (days), and n is the Avrami exponent (dimensionless). Parameters were estimated by nonlinear least-squares fitting using the Levenberg–Marquardt algorithm in R 4.3.1 (package nls2).

Microclimate and soil measurements

Root-zone soil temperature was recorded at 5, 15, and 25 cm depths using PT-1000 RTD sensors (accuracy ±0.1°C) connected to a Campbell CR300 datalogger at 15-min intervals. Volumetric soil water content (SWC) was measured by FDR probes (Sentek EnviroSCAN) at identical depths. Soil CO_2 efflux was quantified biweekly using a LI-COR LI-8100A automated soil gas flux system with a 10-cm survey chamber.

Crop phenological stages (emergence, first true leaf, vine initiation, anthesis, fruit set, commercial maturity) were recorded according to BBCH scale. Marketable yield was determined by hand-harvesting all plots when >85% of fruits showed external maturity indicators; individual fruit mass and total soluble solids (TSS, Brix°) were recorded.

Statistical analysis

Data were subjected to two-way ANOVA (treatment × year) followed by Tukey's HSD post-hoc test at $\alpha = 0.05$ using R package agricolae 1.3.6. Pearson correlations between degradation parameters and microclimate variables were computed across all plot-year combinations ($n = 72$). Regression models were validated by leave-one-out cross-validation.

RESEARCH RESULTS

Degradation kinetics under field conditions

Tensile strength retention curves for all biodegradable films showed a characteristic sigmoidal decline consistent with the Avrami model (Figure 1, model fit statistics in Table 2). The induction period t_0—during which films maintained >80% TS—differed markedly among treatments. TPS films lost structural integrity earliest ($t_0 = 21 \pm 3$ days), followed by PAPER ($t_0 = 34 \pm 4$ days). PBAT showed the longest induction period ($t_0 = 58 \pm 6$ days), closely matched by PHA ($t_0 = 54 \pm 5$ days).

Table 2. Fitted Avrami model parameters for biodegradable film tensile strength degradation

Film	**k (day^{-1})**	**t_0 (days)**	**n (Avrami exp.)**	**T50 (days)***	**T10 (days)****	**R^2**
PLA	0.041 ± 0.004	38 ± 4	2.14	62 ± 5	84 ± 7	0.96
PHA	0.029 ± 0.003	54 ± 5	1.88	78 ± 6	102 ± 8	0.97

Film	**k (day^{-1})**	**t_0 (days)**	**n (Avrami exp.)**	**T50 (days)***	**T10 (days)****	**R^2**
TPS	0.118 ± 0.012	21 ± 3	3.21	38 ± 3	49 ± 4	0.93
PBAT	0.026 ± 0.003	58 ± 6	1.79	88 ± 7	115 ± 9	0.98
PAPER	0.086 ± 0.009	34 ± 4	2.56	52 ± 5	68 ± 6	0.94

** T50 = days to 50% TS retention; ** T10 = days to 10% TS retention (near-complete fragmentation)*

A strong positive correlation was observed between cumulative UV dose at degradation onset and the induction period t_0 ($r = 0.91$, $p < 0.001$), confirming that UV stabilizer concentration is the primary engineering lever controlling initial film longevity under Central Asian irradiance conditions. Specifically, every 100 ppm increase in UV stabilizer concentration extended t_0 by approximately 4.2 ± 0.6 days.

Root-zone microclimate dynamics

Table 3. Mean root-zone temperature (°C) at 5 cm depth and volumetric SWC (%) across full growing season (April–September)

Treatment	**Mean T_{soil} (5 cm, °C)**	**ΔT vs. LDPE (°C)**	**Mean SWC (%, 0–30 cm)**	**CO_2 flux (g CO_2 m^{-2} d^{-1})**	**Weed density (plants m^{-2})**
Bare soil	24.6 b	−2.1	14.8 d	2.41 d	28.4 a
LDPE	26.7 a	0 (ref)	22.4 a	2.68 d	2.1 d
PLA	26.1 ab	−0.6	20.8 ab	3.84 bc	3.8 d
PHA	26.4 ab	−0.3	21.6 ab	3.61 c	3.2 d
TPS	25.2 b	−1.5	17.3 c	5.12 a	11.6 b
PBAT	29.6 a	**+2.9***	21.9 ab	4.87 ab	2.9 d
PAPER	25.8 b	−0.9	18.6 bc	3.22 cd	8.3 c

*Values within a column followed by different lowercase letters differ significantly (Tukey's HSD, $p < 0.05$). * Significantly higher than LDPE ($p < 0.01$).*

The PBAT treatment produced a root-zone temperature at 5 cm depth that was 2.9°C higher than LDPE ($p < 0.01$), attributable to exothermic microbial decomposition activity peaking between days 60–85 post-installation. This temperature elevation coincided with the fruit-fill stage in both crops, accelerating degree-day accumulation and advancing commercial maturity by 6–8 days relative to LDPE. Conversely, TPS and PAPER treatments, which lost structural integrity before canopy closure, allowed inter-row soil evaporation that reduced SWC by 3.8–6.1 percentage points compared to intact film treatments.

Crop performance and yield components

Table 4. Watermelon and cantaloupe marketable yield and fruit quality parameters (means ± SD)

Treatment	**Watermelon yield (t ha^{-1})**	**Cantaloupe yield (t ha^{-1})**	**Mean fruit wt. (kg)**	**TSS (°Brix)**	**Days to maturity**	**Film residue (kg ha^{-1})**
Bare soil	26.2 ± 2.8 d	14.8 ± 1.4 d	5.84 c	9.6 d	88 a	0 d
LDPE	38.6 ± 3.1 b	22.4 ± 2.1 b	8.12 a	11.4 b	80 b	24.8 a
PLA	35.1 ± 2.6 c	20.1 ± 1.8 c	7.68 b	11.0 b	82 b	2.4 b
PHA	36.4 ± 2.9 bc	21.0 ± 1.9 bc	7.84 ab	11.2 b	81 b	1.8 b
TPS	28.4 ± 3.3 d	16.2 ± 1.6 d	6.21 c	9.9 d	85 ab	0.6 c
PBAT	**41.3 ± 3.4 a**	23.6 ± 2.2 a	8.41 a	**12.1 a**	**74 c**	1.2 bc
PAPER	30.8 ± 2.7 d	17.4 ± 1.5 d	6.58 c	10.3 c	84 ab	0 d

Means in a column sharing the same letter do not differ significantly (Tukey's HSD, $p < 0.05$). Film residue = dry mass remaining at crop harvest.

PBAT achieved the highest watermelon marketable yield (41.3 t ha^{-1}), exceeding LDPE by 7.0% ($p < 0.05$). This yield advantage was associated with three concurrent effects: earlier commercial maturity (−6 days vs. LDPE), higher mean fruit TSS (+0.7°Brix), and lower inter-row weed pressure (2.9 plants m^{-2} vs. 2.1 for LDPE, statistically equivalent). TPS and PAPER, whose early degradation exposed the inter-row zone, yielded equivalently to bare soil in cantaloupe ($p > 0.05$), underscoring that premature film failure is agronomically equivalent to no mulching.

DISCUSSION

The most consequential finding of this study is that the thermal bonus attributable to microbial exothermy during PBAT decomposition an additional 2.9°C at 5 cm depth relative to intact LDPE represents a microclimate modification not captured by current film selection protocols, which focus exclusively on radiative and conductive properties of intact films [15]. This exothermic effect accelerated growing degree-day (GDD) accumulation by approximately 120–140 GDD over the 30-day peak decomposition window, which by established cucurbit phenology models corresponds to a 6–8 day advancement in maturity closely matching our observed data.

The Avrami model provided a robust parametric description of field degradation under Central Asian conditions ($R^2 = 0.93–0.98$), validating its applicability outside the temperate European and East Asian contexts for which it was originally calibrated [11, 12]. The markedly higher UV-A irradiance at our site (1,247 kJ m^{-2} yr^{-1} vs. 740 kJ m^{-2} yr^{-1} in Northern Italy) compressed induction periods by a factor of approximately 1.7 relative to manufacturer-published lifespans, indicating that labelling standards based on European test conditions systematically overestimate film longevity in Central Asia by 60–75%.

A practical design criterion emerging from our data is the ‘functional coverage window’ (FCW): the period between film installation and canopy closure, during which intact mulch film is agronomically necessary. For watermelon cv. Crimson Sweet at our site, FCW = 65 ± 4 days. PBAT (t_0 = 58 days, T50 = 88 days) satisfies FCW marginally but reliably; PHA (t_0 = 54 days) is borderline; TPS (t_0 = 21 days) fails critically. We therefore propose a conservative design rule: $t_0 \geq$ FCW + 15 days as a safety margin for regional product certification.

Our CO_2 flux data confirm Li et al.’s [13] linear CO_2–mass-loss relationship in a hyper-arid, low-OM soil context for the first time. The slope of this relationship (3.4 g CO_2 per gram of film decomposed) was 18% lower than reported for temperate soils, likely reflecting the lower microbial biomass carbon (MBC = 84 mg C kg^{-1} in our soil vs. 180–260 mg C kg^{-1} in temperate Cambisols), which slows terminal mineralisation of recalcitrant film fragments.

Limitations include the single-site design and the absence of below-ground residue data beyond the growing season. Multi-site trials spanning Fergana Valley (higher organic matter) and Karakalpakstan (saline soils) are recommended to generalise the Avrami parameterisations. Additionally, life-cycle assessment (LCA) comparing PBAT and LDPE across their full value chains including polymer production energy and end-of-life residue management costs would complete the sustainability case.

CONCLUSION

This study provides the first quantitative characterization of biodegradable mulch film degradation kinetics and associated root-zone microclimate effects under arid Central Asian conditions. PBAT-blend films (25 µm, 1,200 ppm UV stabilizer) were the only biodegradable formulation to satisfy the functional coverage window requirement (FCW = 65 days) while delivering near-zero post-harvest soil residue (1.2 kg ha^{-1} vs. 24.8 kg ha^{-1} for LDPE). The exothermic microclimate bonus during PBAT decomposition (+2.9°C at 5 cm depth) produced a yield premium of 7.0% over LDPE for watermelon, driven by earlier commercial maturity and higher fruit TSS effects attributable to decomposition-derived heating rather than film optical properties. The Avrami model accurately described tensile strength degradation kinetics ($R^2 \geq 0.93$); UV stabilizer concentration was the primary determinant of induction period t_0, with each 100 ppm increase extending t_0 by 4.2 days under local UV-A irradiance. Manufacturer-published film lifespans, calibrated for European conditions, overestimate functional longevity in Uzbekistan by 60–75%, necessitating region-specific certification protocols. The proposed design criterion $t_0 \geq$ FCW + 15 days provides a practical rule for biodegradable film specification in arid cucurbit production systems of Central Asia.

REFERENCES:

1. OECD. (2022). Plastics in Agriculture: Sources, Fates, and Impacts. OECD Publishing, Paris. https://doi.org/10.1787/e1163e2b-en
2. Ministry of Agriculture, Republic of Uzbekistan. (2023). Annual Report on Agricultural Inputs Consumption. Tashkent: MAR Statistical Division. 112 p.
3. Sintim, H.Y., Bandopadhyay, S., English, M.E., et al. (2019). Impacts of biodegradable plastic mulch on soil health. Agriculture, Ecosystems & Environment, 273, 36–49.
4. Ghimire, S., Wszelaki, A.L., Moore, J.C., et al. (2018). The use of biodegradable mulches in lieu of polyethylene in fresh-market tomato production. HortScience, 53(3), 288–294.
5. Moreno, M.M., Moreno, A., Mancebo, I. (2009). Comparison of different mulch materials in a pepper (Capsicum annuum L.) crop. Spanish Journal of Agricultural Research, 7(3), 54–60.
6. Kyrikou, I., Briassoulis, D. (2007). Biodegradation of agricultural plastic films: a critical review. Journal of Polymers and the Environment, 15(2), 125–150.
7. Mochizuki, M. (2010). Synthesis, properties, and structure of poly(lactic acid). In: Auras R. et al. (eds.) Poly(Lactic Acid). Wiley, pp. 17–29.
8. Brodhagen, M., Peyron, M., Miles, C., Inglis, D.A. (2015). Fate of soil-applied bioplastic poly(3-hydroxybutyrate-co-3-hydroxyvalerate). Polymer Degradation and Stability, 114, 46–56.
9. Sintim, H.Y., Bary, A.I., Hayes, D.G., et al. (2020). Release of micro- and nanoplastic fragments from soil-incorporated conventional- and biodegradable-mulch films. Environmental Science & Technology, 54(20), 12828–12839.
10. Moreno, M.M., Moreno, A. (2008). Effect of different biodegradable and polyethylene mulches on soil properties and production in a long-term experiment. Scientia Horticulturae, 117(2), 49–56.
11. Briassoulis, D., Dejean, C. (2010). Critical review of norms and standards for biodegradable agricultural plastics. Journal of Polymers and the Environment, 18(3), 384–400.
12. Morales, M.A., Aranaz, I., Guitart, M., et al. (2022). Modelling UV-induced degradation kinetics of starch-PBAT blend films in Mediterranean field conditions. Polymer Testing, 108, 107498.
13. Li, C., Moore-Kucera, J., Miles, C., et al. (2014). Effects of biodegradable mulch on soil quality. Applied Soil Ecology, 79, 59–69.
14. Bandopadhyay, S., Martin-Closas, L., Pelacho, A.M., DeBruyn, J.M. (2018). Biodegradable plastic mulch films: impacts on soil microbial communities and ecosystem functions. Frontiers in Microbiology, 9, 819.
15. Miles, C., Wallace, R., Wszelaki, A., et al. (2012). Deterioration of potentially biodegradable alternatives to black polyethylene mulch in three tomato production regions. HortScience, 47(9), 1270–1277.