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Physicochemical responses to standard and biodegradable plastic film mulches in a tropical dry-zone Alfisol

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KEYWORDS

Conventional plastic film mulch, plasticulture, soil fertility, sustainable agriculture, tropical agriculture

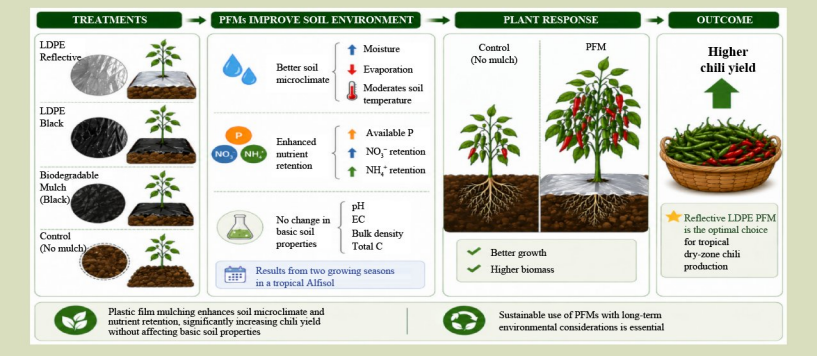
HIGHLIGHTS

- Plastic film mulches (PFMs) did not alter soil pH, electrical conductivity, bulk density and soil total C in a tropical Alfisol.
- PFM enhanced soil available P and mineral N (NO_3^- and NH_4^+) retention.
- Reflective low-density polyethylene (LDPE) PFM most effectively moderated soil temperature, while black biodegradable mulch conserved soil moisture.
- PFMs significantly increased chili yield compared to the control.
- Reflective LDPE PFM was the optimal PFM for tropical dry-zone chili production.

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GRAPHICAL ABSTRACT



ABSTRACT

Agricultural plastic film mulches (PFMs) are widely used to enhance crop productivity by conserving soil moisture, suppressing weeds and regulating soil temperature. Although PFM application is a common management practice for high-value crops in Sri Lanka, the effects of different PFM types on soil properties and agroecosystem functioning remain poorly understood. A two-season field study was conducted to evaluate the impact of three PFM types on soil physicochemical properties and chili (*Capsicum annuum*) performance in an Alfisol, in the dry zone of Sri Lanka, comparing a no-mulch control, reflective low-density polyethylene ($LDPE_{ref}$), black LDPE ($LDPE_{black}$) and black biodegradable mulch (BDM). Sampling was conducted at 0, 4, 8 and 12 weeks after transplanting. The two seasons presented contrasting hydroclimatic conditions, which influenced the magnitude and consistency of treatment effects. PFM application did not significantly affect soil pH, electrical conductivity, bulk density or total carbon. However, both LDPE-PFMs

consistently enhanced soil available phosphorus, $LDPE_{black}$ and BDM promoted nitrate retention, and $LDPE_{ref}$ supported the greatest ammonium retention. Among all treatments, $LDPE_{ref}$ and BDM were most effective in reducing soil temperature and maintaining soil moisture, respectively, under the dry conditions of the region. Chili yield and fresh biomass were significantly higher under all PFM treatments, with highest yields recorded under BDM in growing season 1 and $LDPE_{ref}$ in growing season 2. Overall, $LDPE_{ref}$ gave the most consistent agronomic performance in both growing seasons. Long-term implications of PFM accumulation and degradation for soil health and agroecosystem sustainability in Sri Lanka remain to be established.

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1 Introduction

Rapid global population growth and the associated rise in food demand are placing substantial pressure on agricultural systems, driving the intensification of existing cropland and the expansion of production into more marginal areas. This has led to the widespread adoption of plastics across the agricultural sector. Global agricultural plastic consumption is estimated at 12.5 $Mt{\cdot}yr^{-1}$, of which plastic film mulches (PFMs) represent the single largest category at about 6.1 $Mt{\cdot}yr^{-1}$[1]. Here, agricultural plastic consumption refers to the total amount of plastic materials used within the agricultural sector and intensive agricultural plastic application describes the extensive use of plastic-based technologies in high-input production systems to enhance crop productivity, water-use efficiency and crop protection. This growth has been driven by the need to improve resource use efficiency, reduce production losses and maximize yields from limited land and water resources. The most common applications of plastics in intensive agriculture include PFMs, greenhouse coverings and polytunnels, packaging and storage materials, and pipes for irrigation[2]. Of these, PFMs contribute to weed and pest control, modify soil temperature, promote organic matter decomposition, reduce evaporation and minimize soil erosion[2–4]. The application of PFMs under the ridge and furrow system also promotes soil water collection and retention[5].

PFMs are available in a wide range of colors, thicknesses and materials, with the majority manufactured from polyethylene (PE) polymers such as low-density polyethylene (LDPE), high-density polyethylene and linear low-density polyethylene[6–9]. These PE-based polymers are the most widely used materials for agricultural mulch films globally, due to their flexibility, durability and cost-effectiveness[2,6]. In this study, LDPE was selected as the comparator plastic mulch material as it is widely used in commercial vegetable production due to its proven ability to improve soil conditions and crop performance[6]. However, the widely-used PE PFMs are typically non-recyclable after use, and their UV-driven fragmentation and incomplete retrieval lead to the progressive accumulation of macro- and microplastic residues in agricultural soils, with documented negative effects on soil structure, water infiltration and microbial community function.

Beyond their primary purpose in modifying the microclimate, these diverse mulch types alter soil physicochemical properties and microbial dynamics. Standard PE films, characterized by their high thermal and moisture retention, often alter soil structural integrity and nutrient cycling, which can subsequently shift the habitat conditions for indigenous microbial communities. In contrast, biodegradable mulches (BDMs) and photo-degradable alternatives have emerged as more sustainable alternatives to LDPE, designed to be incorporated into the soil after harvest and degrade under natural environmental conditions[3,6]. As these materials decompose, they introduce organic matter directly into the soil-plant system, potentially fostering different microbial activity patterns and nutrient cycling rates compared to standard LDPE films. Integrating these physical and biological dimensions is essential for evaluating the long-term impact of mulch technologies on soil health within agroecological systems. However, evidence suggests that BDMs often degrade slower than anticipated in realistic field conditions, failing to meet established biodegradation standards[10–12]. For example, the international biodegradation standard EN 17033 requires that 90% of the carbon in the plastic polymer is degraded

within 2 years under aerobic conditions in a laboratory setting[11,13]. However, under field conditions, this process can take 21 to 58 months to reach the 90% threshold[11].

The dry zone covers about 70% of Sri Lanka's total land area and represents the country's principal agricultural region[14]. It receives a mean annual rainfall of < 1750 mm, with a pronounced dry season from May to September, high daily pan evaporation rates of 2.5–8.0 mm·d^{-1} driven by warm desiccating winds, and a mean annual sunshine duration of 4.3–9.3 h·d^{-1}, with peak irradiance occurring between February and April[15]. These climatic conditions create significant challenges for rainfed agriculture, making soil moisture conservation a critical determinant of crop productivity[16]. PFMs offer considerable potential in this context, as they can enhance crop growth and yield by modifying the soil microenvironment and nutrient dynamics, reducing evaporative losses, mitigating erosion during high-intensity rainfall events and influencing the size, structure and activity of the soil microbial community[8].

However, despite their widespread use in intensive vegetable systems in Sri Lanka, the impact of different PFM types on soil properties, agroecosystem function, and PFM breakdown and fate in this climate zone remains poorly understood. In particular, no field-based study has directly compared the agronomic performance and physical integrity of standard LDPE PFM and BDM consisting of polylactic acid/polybutylene adipate-*co*-terephthalate (PLA-PBAT) across multiple growing seasons under the semiarid conditions of South Asian dry zone agriculture.

Therefore, we conducted a field study over two growing seasons to assess the impact of three different PFM types on soil physicochemical properties and crop performance (*Capsicum annuum*) in an Alfisol, in the dry zone of Sri Lanka. We compared a control treatment (no PFM), reflective LDPE PFM ($LDPE_{ref}$), black LDPE PFM ($LDPE_{black}$), and black BDM. We hypothesize that (1) the application of PFMs will alter soil physicochemical properties and positively impact plant performance compared to the control, and (2) that standard LDPE PFMs will outperform the BDM due to faster fragmentation of BDM over time. The findings of this study will provide evidence-based guidance for PFM selection in semiarid smallholder systems and contribute to broader efforts to balance agricultural productivity with plastic pollution mitigation in tropical developing-country contexts.

2 Materials and methods

2.1 Experimental site

The experiment was conducted at the Field Crop Research and Development Institute (FCRDI) (8°6′42″ N, 80°28′1″ E), Mahailluppallama, Sri Lanka. The soil is classified as a Typic Rhodustalf (US Soil Taxonomy) or a Reddish Brown Earth great soil group under the Sri Lanka classification system[17]. Weather data for the site were obtained by the Meteorological Department of FCRDI, Mahailluppallama, Sri Lanka. The daily minimum and maximum temperatures during growing seasons 1 and 2 were 25.6 and 36.8 °C, and 25.0 and 37.4 °C, respectively, while the annual rainfall was < 1750 mm in both seasons.

2.2 Experimental setup

Plants were grown in two seasons, in 2023 (June-September) and 2024 (March-June). In total, 16 plots (1 m × 4 m) were established with four replicates per treatment in a randomized complete block design (Fig. 1). The same plots and treatment allocations were maintained in both growing seasons to mimic typical agronomic practices and to assess potential short-term cumulative effects. The selected field had no prior record of agricultural plastic use. The PFMs used were: $LDPE_{ref}$ PFM with silver on top and black on the bottom had a thickness of 30 μm sourced from Hayleys Agriculture Holdings Ltd., Sri Lanka; $LDPE_{black}$ PFM was 30 μm thick and sourced from Gro-Clean GroMax Industries Ltd., UK; and BDM consisting of a 15% PLA and 85% PBAT with a polybutylene sebacate adhesive[18], and thickness of 15 μm also sourced from Gro-Clean GroMax Industries Ltd.

The field was prepared by plowing to 20 cm and with plots in a ridge and furrow system, which is standard agronomic practice in the region. All agronomic practices adhered to recommendations issued by the Department of Agriculture (DoA), Sri Lanka[19]. One week before transplanting, triple superphosphate at 100 kg·ha^{-1} and potassium chloride at 50 kg·ha^{-1} were applied as a basal dressing in line with DoA recommendations for chili production on Alfisols in Sri Lanka[19]. Seeds of *Capsicum annuum* (chili cv. MICH HY 01) were germinated in a nursery and seedlings transplanted into the field after 28 days in both growing seasons. PFMs featuring pre-punched planting holes (15 cm diameter) were placed over

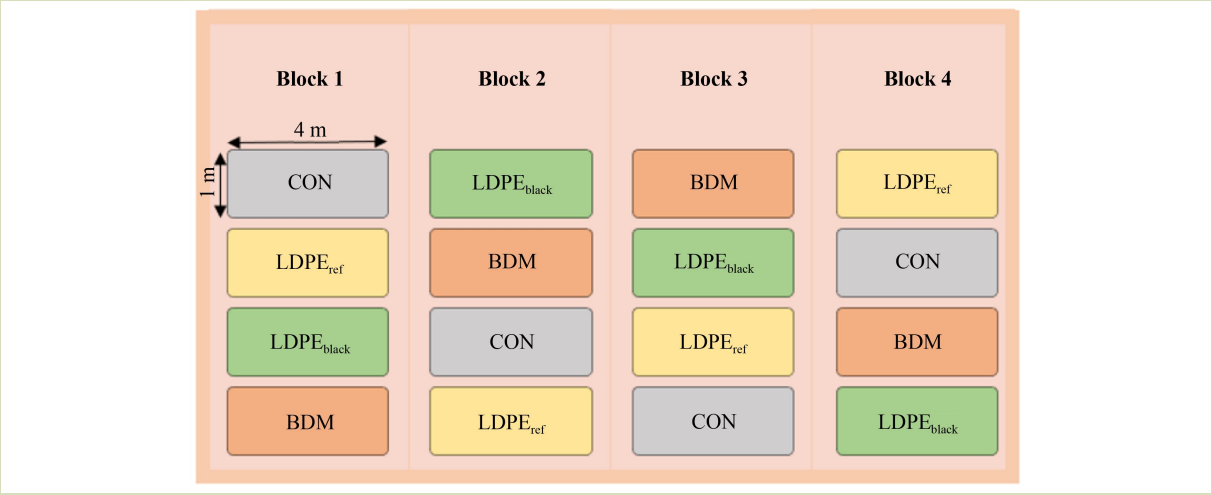


Fig. 1 Layout of experimental plots in a randomized complete block design, used for the field experiment with control (CON), reflective low-density polyethylene (LDPE$_{ref}$), black low-density polyethylene (LDPE$_{black}$), and black biodegradable PLA-PBAT (BDM) treatments.

the respective plots and the edges were buried in the soil to secure them. PFMs were replaced with new material before the commencement of the second growing season. Seedlings were transplanted at a density of 20 plants per plot.

Nitrogen fertilizer was applied as urea top dressings at 2 weeks after transplanting (WAP) (100 kg·ha^{-1}), 4 WAP (125 kg·ha^{-1}), 8 WAP (125 kg·ha^{-1} urea + 50 kg·ha^{-1} potassium chloride), and 12 WAP (125 kg·ha^{-1}), following DoA recommendations. All fertilizer rates are expressed as the fertilizer compound quantities to reflect field application practices, while the corresponding elemental nutrient contents were about 46% N in urea and 50% K in potassium chloride. Fertilizer granules were distributed evenly into each planting hole. Irrigation was delivered via a sprinkler system daily during the first three days; thereafter, supplementary irrigation was applied only on rain-free days.

2.3 Soil and plant sampling

Soil sampling was conducted at 0, 4, 8 and 12 WAP, prior to fertilizer application at each time point, and samples were taken from three random locations within the planting holes in each plot to 20 cm. These soil samples were homogenized, air-dried at room temperature, gently crushed with a mortar and pestle and sieved (2 mm) prior to analysis. Freshly-collected soil samples were used to prepare soil extractions for nitrate and ammonium determination. Soil bulk density samples (100 mL) were collected from three depth intervals: 0–10, 10–20 and 20–30 cm at the end of each growing season.

Chili yield was recorded weekly from 8 WAP, once the fruit had reached the dark green stage, on six arbitrarily selected plants per plot. At the end of each growing season, six plants were arbitrarily selected from each plot and harvested by pulling the whole plant, including the roots, from the soil. Fresh biomass was recorded after removal of soil adhering to the roots. Plants were then separated into roots, fruits, stems and leaves. Plant samples were oven-dried at 80 °C until constant weight was reached. Dry biomass was recorded and samples were ground into a fine powder using a grinding mill for further chemical analysis.

2.4 Soil and plant analysis

Soil pH and electrical conductivity (EC) were measured in soil suspensions prepared at a 1:2.5 freshly-collected soil:distilled water (w/v) ratio at 25 °C, following standard protocols[20]. Soil bulk density was determined on oven-dried cores (105 °C, 48 h) using a core sample method[20]. Soil gravimetric moisture content was determined by mass loss after oven-drying at 105 °C for 48 h to constant weight. Soil volumetric moisture content and temperature were recorded continuously at hourly intervals using Acclima TDT Soil-Water-Temperature SDI-12

sensors (Acclima Inc., Meridian, ID, USA) installed at a soil depth of 15 cm.

Soil NH_4^+ and NO_3^- concentrations were measured in 1:5 (w/v) fresh soil: 1 mol·L^{-1} KCl extracts using the salicylate method of Mulvaney (1996)[21] and VCl_3 reduction method of Miranda et al.[22], respectively. Soil available P (Olsen P) was determined in a 1:5 soil:0.5 mol·L^{-1} $NaHCO_3$ extracts using the molybdate blue method[23]. The total C content of the soil and plant samples was determined using a Series 2400 CHN Elemental Analyzer (PerkinElmer, Waltham, MA, USA).

Leaf chlorophyll content was measured biweekly until 8 WAP using a SPAD chlorophyll meter (SPAD-502 PLUS, Konica Minolta, Tokyo, Japan). Plant total N and P were determined by Kjeldahl digestion method[24,25]. Plant dry biomass was determined on six arbitrarily selected plants per plot after oven-drying at 80 °C for 24 h.

2.5 Data analysis

For all statistical analyses, plots (n = 4) were used as the experimental units, except for soil temperature and moisture, for which data were obtained from three replicate plots per treatment. Prior to analysis, all data were tested for normality using the Shapiro-Wilk test and for homogeneity of variance using Levene's test. Single time-point measurements, including soil bulk density, total plant dry biomass, root and shoot biomass fractions, total plant N, total plant P, total plant C, total soil C, and cumulative seasonal chili yield, were analyzed using one-way analysis of variance followed by Tukey's multiple range test ($p \leqslant 0.05$) in Minitab (v17.0; Minitab LLC, State College, PA, USA). Soil temperature and moisture data were analyzed using a general linear model with treatment and time as fixed factors, followed by Tukey's multiple comparison test ($p \leqslant 0.05$) in Minitab (v17.0; Minitab LLC, State College, PA, USA).

Repeated measures data, including soil available P, NO_3^- and NH_4^+, and leaf chlorophyll content (SPAD), were analyzed using a linear mixed model in Minitab, with mulching treatment (control, $LDPE_{black}$, $LDPE_{reflective}$ and BDM) and sampling time (0, 4, 8 and 12 WAP) as fixed, interacting factors and replicates as random effects. When significant effects were found ($p < 0.05$), Tukey's post hoc test was used for pairwise mean comparisons. Treatment differences were tested within the same growing season.

3 Results and discussion

3.1 Weather data

During the first growing season (June–September 2023), mean daily air temperature remained relatively stable at 28–30 °C (Fig. 2(a)), while precipitation was low throughout (< 2.5 mm·d^{-1}), with the exception of a marked increase in September (Fig. 2(c)). This resulted in generally dry conditions during the early and mid-stages of crop growth. Correspondingly, relative humidity ranged from 74% to 95%, with an increase in September reflecting the late-season rainfall (Fig. 2(e)). Given the limited rainfall during this season, supplemental irrigation was applied uniformly across all plots to maintain adequate soil moisture levels. During the second growing season (March–June 2024), mean daily air temperature was comparable, ranging from 28–31 °C (Fig. 2(b)). Precipitation was markedly higher and more variable, with a distinct peak in midseason (Fig. 2(d)), which reduced the requirement for supplemental irrigation. Overall, the two seasons presented contrasting hydroclimatic conditions: growing season 1 was characterized by persistently high temperatures and low, episodic rainfall, whereas growing season 2 experienced greater precipitation frequency and humidity. These contrasting conditions are likely to have influenced soil moisture dynamics, nutrient availability and crop performance, and are considered in the interpretation of results throughout this section.

3.2 Soil responses

3.2.1 Impact of PFMs on soil pH and EC

The application of PFM did not result in a consistent or long-term effect on soil pH relative to the control in either growing season. While there were statistically significant differences between treatments in certain time points, most notably at 12 and 8 WAP in first and second growing seasons, respectively. These changes were transient and did not follow a clear, consistent pattern between seasons (Table 1). Nevertheless, our findings align with those in the literature[26,27], which indicate that PFM application typically does not result in long-term changes in soil pH and generally does not cause sustained shifts in soil pH. The observed variations in pH were probably due to regional environmental heterogeneity or microbial responses to the mulch degradation process.

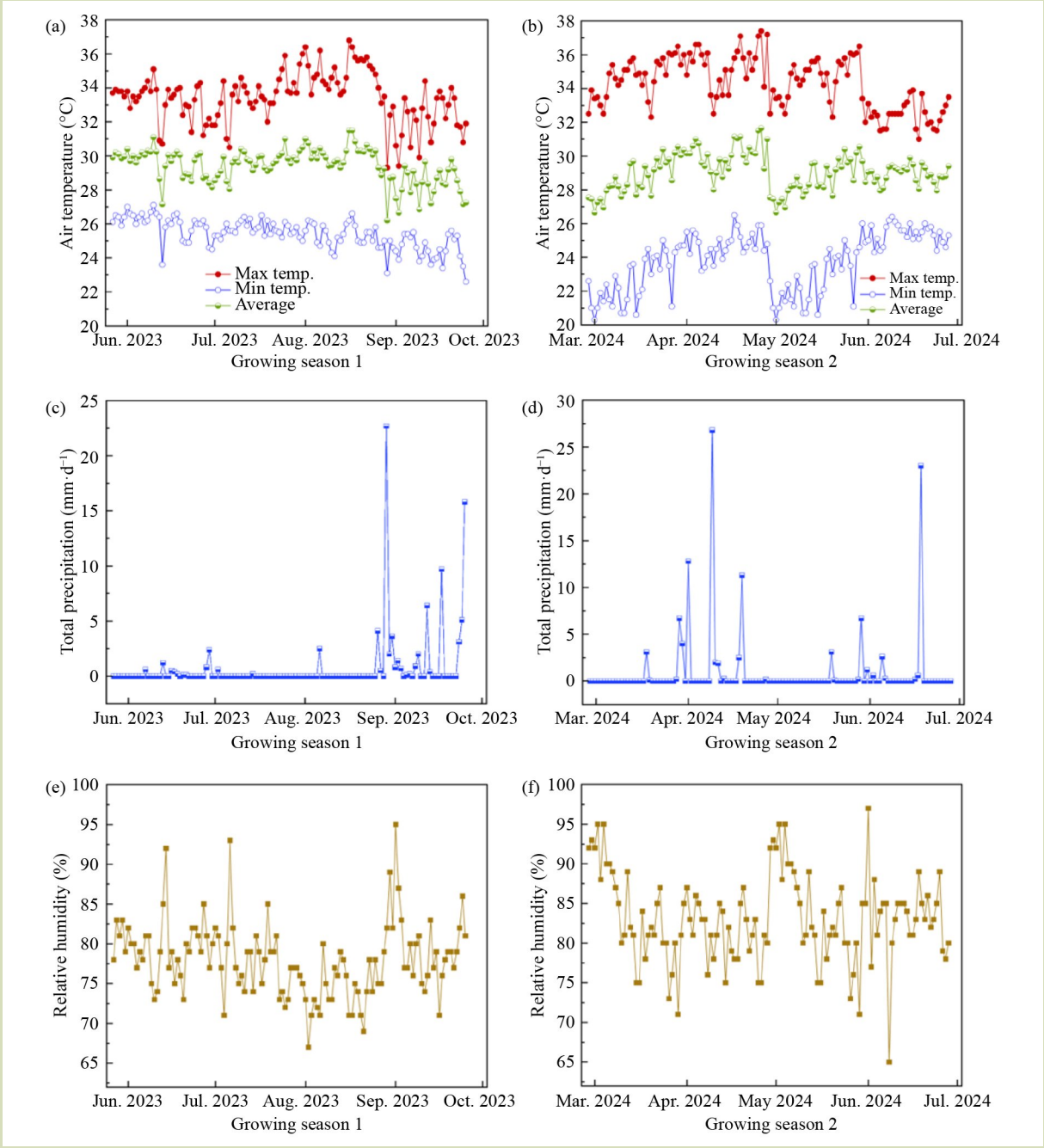


Fig. 2 Daily maximum, minimum and average temperature for growing seasons 1 (a) and 2 (b); daily total precipitation for growing seasons 1 (c) and 2 (d); and daily relative humidity for growing seasons 1 (e) and 2 (f).

Soil EC was similarly unaffected by PFM treatment in both growing seasons relative to the control (Table 1). Although $LDPE_{black}$ and BDM treatments gave transient increases in EC at isolated time points, EC values converged across treatments by 12 WAP, indicating that PFM application did not promote progressive salt accumulation in the soil profile. This moderating effect on soil salinity may help sustain balanced nutrient availability while reducing the risk of salt-induced

Table 1 Soil pH and electrical conductivity (EC) measured under chili cultivation in control (CON), $LDPE_{ref}$, $LDPE_{black}$ and BDM treatments at 0, 4, 8 and 12 weeks after transplanting (WAP) in two growing seasons

Growing season	Treatment	Soil pH				Soil EC (μS·cm^{-1})			
		0 WAP	4 WAP	8 WAP	12 WAP	0 WAP	4 WAP	8 WAP	12 WAP
1	CON	6.99±0.05a	6.89±0.3b	6.58±0.32a	6.33±0.04b	68±2.58a	70±12.1b	199±3.04a	96±18.98a
	$LDPE_{ref}$	7.01±0.09a	7.36±0.7ab	6.77±0.45a	6.39±0.07b	73±8.50a	116±29.3b	148±12.1a	80±28.04a
	$LDPE_{black}$	7.11±0.03a	7.98±0.3a	7.17±0.21a	6.31±0.23b	77±19.0a	162±8.34a	126±9.56a	77±1.06a
	BDM	7.11±0.06a	7.79±0.4ab	7.11±0.30a	6.84±0.06a	77±12.69a	108±18.5b	178±14.9a	87±26.01a
2	CON	6.87±0.03a	7.14±0.1a	7.17±0.04a	6.98±0.16a	128±32.5a	101±34.9ab	59±3.79a	59±10.6a
	$LDPE_{ref}$	6.86±0.10a	6.90±0.1a	7.05±0.05b	6.97±0.05a	102±12.7a	65±14.47b	46±5.00a	59±19.6a
	$LDPE_{black}$	6.78±0.10a	7.01±0.1a	6.92±0.06c	7.03±0.05a	93±12.1a	74±19.53b	44±4.92a	40±5.00a
	BDM	6.73±0.04a	6.93±0.2a	6.81±0.04d	7.12±0.34a	87±11.7a	128±23.5a	56±9.45a	45±5.92a

Note: Within each sampling occasion and growing season, means followed by the same letter are not significantly different (Tukey's test, $p \leqslant 0.05$). Values are mean ± SD ($n = 4$).

crop stress. These findings are consistent with those of Dewi et al.[28], who reported no significant effect of LDPE or biodegradable PFM residue incorporation on soil EC in a greenhouse pot experiment.

3.2.2 Impact of PFMs on soil bulk density

No significant differences in bulk density were detected across treatments at any depth in either growing season (Fig. S1), indicating that PFM application did not induce soil compaction over the experimental period. These findings are consistent with those of Sintim et al.[29], who reported no significant change in soil bulk density over a 4-year field study using biodegradable and PE PFMs, and with Domagała-Świątkiewicz and Siwek[30], who found no significant effect of PFM application on bulk density in leek and onion cultivation. These results indicate that surface application of PFMs does not measurably alter soil bulk density, at least over short-to-medium experimental timescales.

3.2.3 Impact of PFMs on soil temperature and moisture

Soil temperature and moisture are widely recognized as the most important microclimate factors influencing crop productivity[31], given their direct effects on soil biochemical processes and plant physiological responses[32,33]. The extent to which PFMs modify these parameters depends on their color, thickness and material composition, which together determine the transmission of ultraviolet (UV) and visible light wavelengths and the associated surface energy balance[31]. $LDPE_{ref}$ films transmit relatively little UV and visible radiation, promoting cooler soil conditions, whereas $LDPE_{black}$ absorbs a greater proportion of incoming radiation, elevating soil temperature. Biodegradable films typically exhibit intermediate optical properties, though their thermal behavior varies with polymer composition and film thickness.

The relative optical behavior of the PFMs used in this study can be inferred from their material characteristics. Based on established optical responses of PE mulches, the expected hierarchy for light penetration is $LDPE_{ref}$ < $LDPE_{black}$ < BDM, with reflective films transmitting the least UV and visible radiation and BDM films allowing greater penetration owing to their lower optical density. In terms of heat absorption, $LDPE_{ref}$ films are expected to absorb the least energy, followed by BDM, with $LDPE_{black}$ absorbing the most due to its higher absorptivity. These differences provide a basis for contextualizing the observed microclimatic effects among mulch types in this study.

Overall, PFM application positively influenced soil microclimatic conditions in both growing seasons (Figs. 3 and 4), with treatment differences in soil temperature and moisture reflecting the contrasting optical and thermal properties of each PFM type and the prevailing seasonal weather patterns. Across growing seasons, mean soil temperature differed significantly among PFM treatments (growing seasons 1 and 2 both: $p < 0.001$). In both growing seasons, $LDPE_{black}$ gave the highest soil temperatures, consistent with its greater solar radiation absorption (Fig. 3). In contrast, $LDPE_{ref}$ maintained

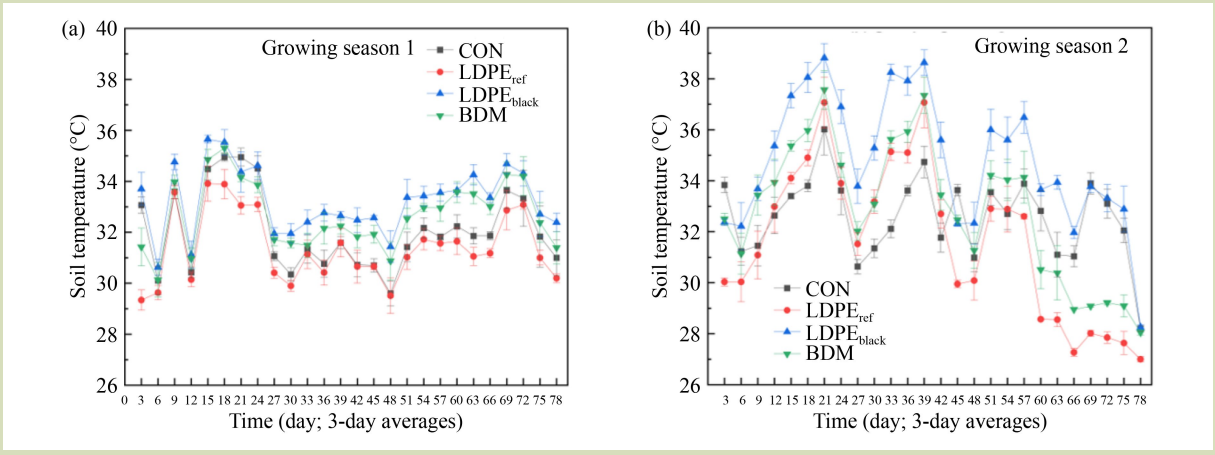


Fig. 3 Three-day mean soil temperature recorded at 15 cm depth during growing seasons 1 (a) and 2 (b) for control (CON), reflective low-density polyethylene (LDPE$_{ref}$), black low-density polyethylene (LDPE$_{black}$), and black biodegradable PLA-PBAT (BDM) treatments. Values are expressed as means± SE (n = 3).

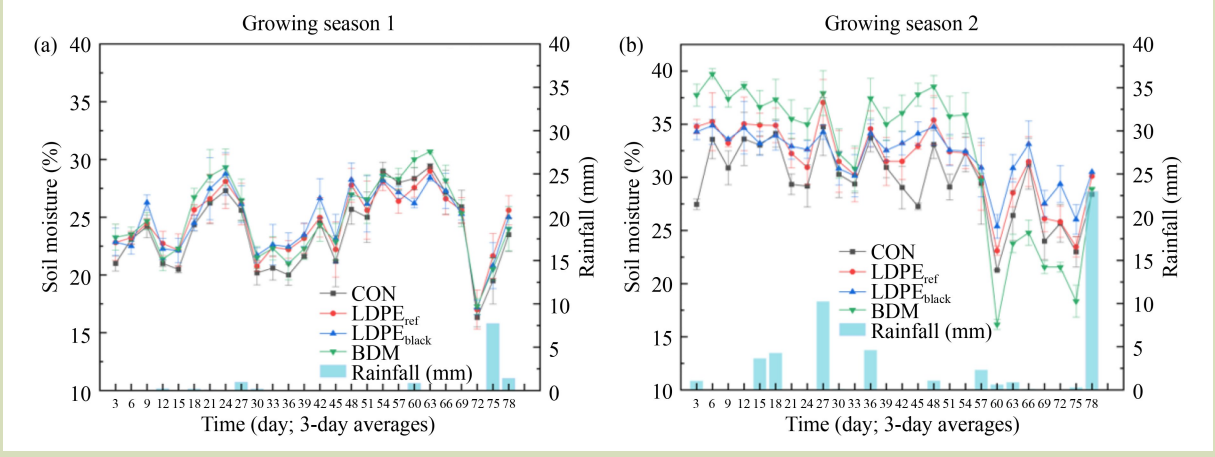


Fig. 4 Three-day mean soil moisture content (%) recorded at 15 cm depth during growing seasons 1 (a) and 2 (b) for control (CON), reflective low-density polyethylene (LDPE$_{ref}$), black low-density polyethylene (LDPE$_{black}$), and black biodegradable PLA-PBAT (BDM) treatments. Vertical bars represent 3-day mean rainfall (mm). All treatment plots received a uniform irrigation frequency and rate throughout the study period. Values are mean ± SE (n = 3).

the lowest soil temperatures, attributable to its high surface reflectivity, while BDM maintained intermediate conditions between LDPE$_{black}$ and the control.

It is important to distinguish between the effects of light penetration and heat absorption when interpreting these patterns. LDPE$_{ref}$ films have high reflectivity across a broad wavelength range (300–800 nm) owing to UV-reflective additives[34], which substantially reduces UV and visible light transmission to the soil surface. Conversely, LDPE$_{black}$ efficiently absorbs UV, visible and near-infrared wavelengths[35], minimizing light transmission while maximizing heat absorption and elevating soil temperatures. These findings are consistent with those of Snyder et al.[31], who reported that reflective PFMs reduced soil temperature relative to bare soil by reflecting UV radiation upward towards

the plant canopy whereas black PFMs increased soil temperature compared to unmulched controls. Quantitatively, reflective PFMs have been shown to reduce soil temperature by up to 8 °C under peak irradiance conditions[31] whereas black PFMs have been reported to increase soil temperature by 1.7–2.8 °C relative to bare soil[36]. Previous studies further confirm that black films retain more heat than lighter-colored or reflective alternatives, including olive, silver, white and blue films[37]. Amongst all PFM types, transparent films provide the greatest soil warming potential, as they transmit the majority of incoming UV and visible radiation while trapping longer-wavelength infrared radiation beneath the film. Under the hot, dry conditions characteristic of the Sri Lankan dry zone, excessive soil warming may be counterproductive to crop growth, particularly during the early establishment stages when plants are most sensitive to temperature changes[38–40]. Overall, PFMs modulate the soil thermal environment through the combined effects of light transmission and heat retention[31], both of which operate throughout the growing season to shape the soil microclimate experienced by the crop.

Soil moisture dynamics in both growing seasons were significantly influenced (growing season 1, $p = 0.003$; growing season 2, $p < 0.001$) by the interaction between water input and the physical barrier provided by the PFMs (Fig. 4). During the first growing season, rainfall was minimal and relative humidity remained below 85%. Under these drier conditions, all PFM treatments effectively conserved soil moisture relative to the control (Fig. 4(a)), with BDM maintaining the highest average soil moisture followed by $LDPE_{black}$ and $LDPE_{ref}$ PFM, with the control the lowest. Given that a uniform irrigation regime was applied across all plots throughout the growing period, the observed moisture conservation in mulched plots can be attributed directly to the physical suppression of soil evaporation by the PFM surface. This is consistent with previous findings demonstrating that PFMs reduce soil evaporation[41,42], which in turn moderates soil cooling through evaporative processes and reduces the net irrigation requirement.

During the second, wetter growing season, soil moisture was elevated across all treatments owing to more frequent and substantial rainfall events (Fig. 4(b)). Under these conditions, BDM and $LDPE_{ref}$ treatments maintained higher post-rainfall soil moisture relative to the control (Fig. 4(b)), indicating that these PFM types are particularly effective at retaining moisture following precipitation events. Notably, no clear relationship between soil moisture, temperature and mulch color was identified under these specific field conditions[39], indicating that the thermal and hydrological effects of PFMs may operate somewhat independently under variable rainfall regimes.

Overall, PFMs modified soil microclimatic conditions in both seasons by reducing evaporative losses and influencing soil temperature and moisture dynamics, with BDM and $LDPE_{ref}$ emerging as the most effective treatments for maintaining favorable soil moisture conditions and lower mean soil temperatures relative to other treatments. This indicates improved soil microclimatic conditions under these treatments may contribute to reduced crop water-stress. However, it should be noted that these outcomes may vary under different climatic regimes, given that regional environmental conditions have been shown to substantially influence the soil microclimate effects of PFMs[31]. Further investigation across diverse agroecological zones would be valuable to confirm the broader applicability of these findings.

3.2.4 Impact of PFMs on soil total carbon

Plastic mulching can influence soil C through both direct and indirect mechanisms[43], although the magnitude and direction of these effects depend on PFM type, duration of application and prevailing environmental conditions[44,45]. PFMs modify the soil microclimate by elevating soil temperature and moisture, which can stimulate root growth and microbial activity, indirectly influencing soil C dynamics[43]. However, the same increases in temperature and moisture may also accelerate organic matter decomposition, potentially reducing soil organic C stocks over time. Biodegradable PFMs may contribute less direct C input to the soil than standard films, but their mineralization by the soil microbial community may stimulate microbial activity and influence the soil organic C pool over longer timescales[43]. Samphire et al.[46] reported that BDMs can accelerate soil organic matter (SOM) turnover and alter soil microbiome composition, but found no significant effect of BDM application on SOM content or bacterial diversity over a three-year field experiment. Conversely, Shah and Wu[8] reported that PFMs can enhance soil organic C content relative to unmulched soil, which they attributed to greater crop biomass inputs under mulched conditions.

In the present study, soil total C increased between the start and end of each growing season across all treatments; however, there were no significant differences between PFM types in

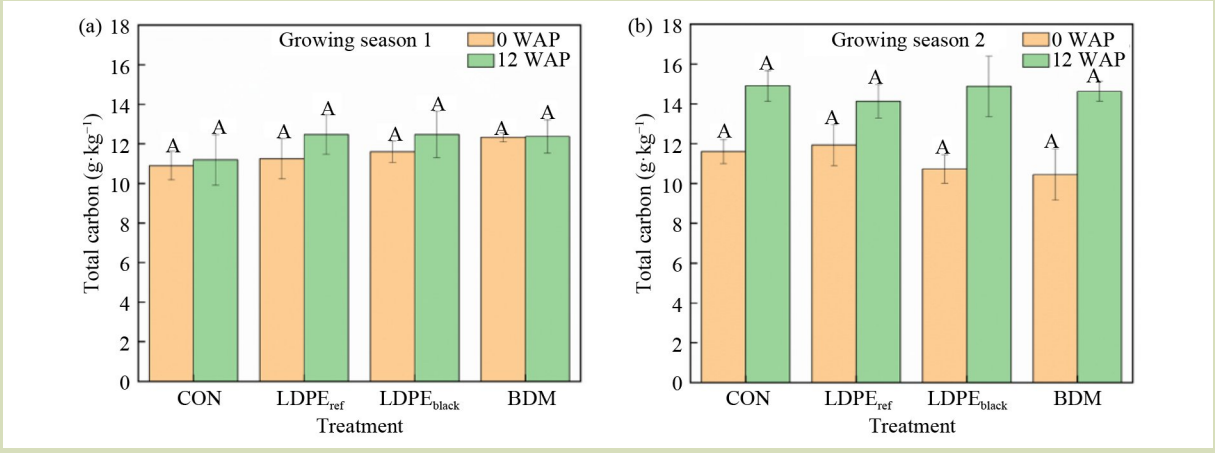


Fig. 5 Total soil carbon at the start (0 WAP) and end (12 WAP) of growing seasons 1 (a) and 2 (b) in control (CON), reflective low-density polyethylene (LDPE$_{ref}$), black low-density polyethylene (LDPE$_{black}$), and black biodegradable PLA-PBAT (BDM) treatments. Means with the same letters are not significantly different between treatments. Values are mean ± SD (n = 4).

either season (Fig. 5). The relatively short duration of the study may have limited the detection of treatment-driven changes in soil C, as the effects of PFM fragmentation and degradation on C dynamics are likely to occur over longer timescales[47]. This is particularly relevant for BDMs, which undergo faster physical fragmentation and microbial mineralization than standard LDPE films. Biodegradable PFMs typically contain ester bonds or polysaccharide-based constituents that are susceptible to microbial hydrolysis[48]. These films may be derived from biological or fossil-based sources[49], with the most widely used compounds including PLA, starch, cellulose, polyhydroxyalkanoates and fossil-based polyesters such as polybutylene succinate, polybutylene succinate-co-adipate and PBAT[49,50]. The progressive mineralization of these materials by the soil microbial community has the potential to alter both the size and composition of the soil organic C pool over time[51].

3.2.5 Impact of PFMs on soil nutrient availability

The effects of PFMs on soil nutrient availability reported in the literature are highly variable, reflecting the influence of environmental conditions, soil type, crop species and PFM type on nutrient cycling processes[52]. Soil available P had significant temporal changes in both growing seasons, with statistically significant for all effects of PFM treatment (p < 0.001), time (p < 0.001) and their interaction (p < 0.001) (Fig. 6(a,b)). Available P increased markedly at 8 WAP in both seasons across all treatments. Although no treatment maintained a continuous upward trend, LDPE$_{ref}$ and LDPE$_{black}$ consistently supported significantly higher soil P concentrations at 8 WAP in growing season 1, whereas BDM and control exhibited comparatively lower values (Fig. 6(a)). In growing season 2, the treatment differences were most pronounced at 8 WAP, with LDPE$_{ref}$ recording the highest available P, followed by LDPE$_{black}$, whereas BDM and control had significantly lower concentrations (Fig. 6(b)). Although P concentrations declined significantly between 8 and 12 WAP in growing season 1, they remained higher during this period in growing season 2, indicating that prevailing environmental conditions between seasons are important for governing soil P retention dynamics.

Soil NO_3^- concentrations were also significantly affected by PFM treatment (p < 0.001), time (p < 0.001) and their interaction in both seasons (p < 0.001), indicating that the efficacy of PFM treatments on mineral N availability is not constant over time (Fig. 6(c,d)). In growing season 1, BDM recorded the highest NO_3^- concentration at 8 WAP, with the control remaining the lowest throughout (Fig. 6(c)). This pattern is consistent with the rapid hydrolysis of urea to NH_4^+ and subsequent nitrification under warm soil conditions[53], and may be further promoted by the partial degradation of BDM, which releases labile C substrates that stimulate microbial activity and enhance urea hydrolysis and nitrification rates.

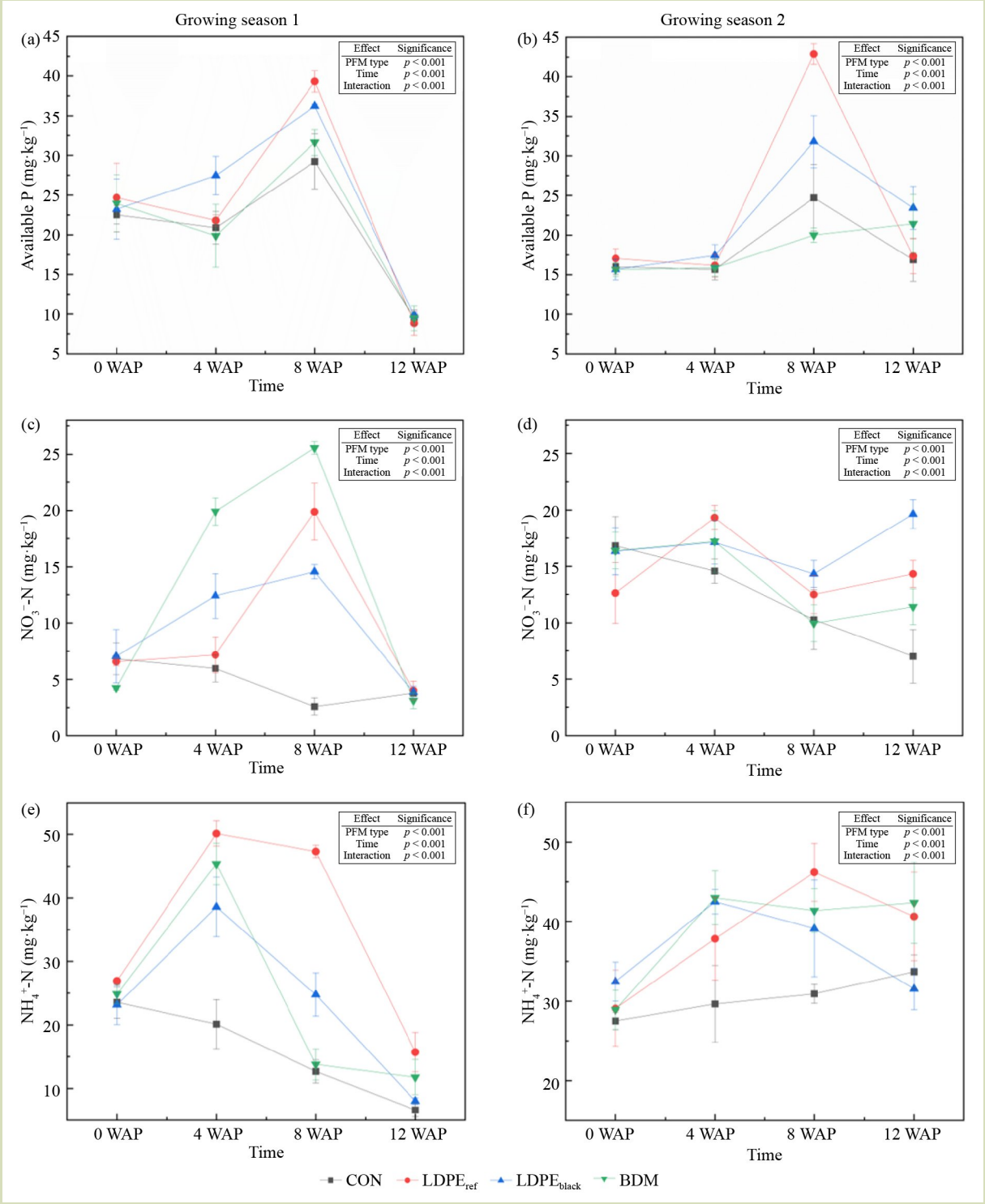


Fig. 6 Dynamics of soil available P for growing seasons 1 (a) and 2 (b); nitrate for growing seasons 1 (c) and 2 (d); and ammonium for growing seasons 1 (e) and 2 (f), under control (CON), reflective low-density polyethylene ($LDPE_{ref}$), black low-density polyethylene ($LDPE_{black}$), and black biodegradable PLA-PBAT (BDM) treatments at 0, 4, 8 and 12 WAP. Values are mean ± SD (n = 4).

This pattern was not repeated in growing season 2. Instead, $LDPE_{ref}$ and $LDPE_{black}$ emerged as the most effective treatments for sustaining mineral N availability during the reproductive stages of crop growth (Fig. 6(d)). Across all PFM treatments, NO_3^- concentrations at 12 WAP were significantly higher than in the control ($p < 0.001$), likely reflecting the capacity of PFMs to reduce N leaching losses[54]. The wetter conditions characteristic of growing season 2 may have promoted greater leaching and denitrification in unmulched control plots, thereby reducing soil NO_3^- accumulation. These divergent seasonal outcomes indicate that the performance and stability of PFM effects on N retention are strongly governed by seasonal variation in soil temperature and moisture, which regulate N transformation and organic matter decomposition processes.

Soil NH_4^+ concentrations were similarly subject to significant effects of PFM treatment ($p < 0.001$), time ($p < 0.001$) and their interaction in both seasons ($p < 0.001$) (Fig. 6(e,f)). In growing season 1, the highest NH_4^+ concentrations were recorded at 4 and 8 WAP, with $LDPE_{ref}$ supporting the greatest concentrations, followed by BDM and $LDPE_{black}$, whereas the control was the lowest throughout (Fig. 6(e)). These results indicate that urea hydrolysis elevated soil NH_4^+ in the early-to-mid growing period, and that PFM-mediated moderation of soil temperature and moisture suppressed NH_3 volatilization losses, thereby enhancing NH_4^+ retention. In growing season 2, $LDPE_{ref}$, $LDPE_{black}$, and BDM all supported significantly higher NH_4^+ concentrations than the control at 4 and 8 WAP ($p < 0.001$) (Fig. 6(f)), indicating that the soil conditions during this season further promoted NH_4^+ retention, potentially through PFM-mediated suppression of nitrification.

Collectively, these results indicate that PFM application enhances soil NO_3^- and NH_4^+ retention, with implications for long-term soil fertility and nutrient use efficiency across multiple growing seasons. These findings are further supported by Yang et al.[55], who demonstrated in an incubation study that plastic debris significantly stimulated microbial respiration and the activities of urease and phosphatase enzymes, processes that are central to N and P cycling. Overall, PFM type exerts a significant influence on soil nutrient dynamics, and understanding the interaction between PFM properties and the soil environment across a broader range of tropical agroecosystems will be important for optimizing soil fertility management under such conditions.

3.3 Plant responses

3.3.1 Impact of PFMs on leaf chlorophyll and plant total P, N and C concentrations

Leaf chlorophyll values were low across all treatments during the early growth stages and increased progressively with plant development. However, no significant differences were detected among treatments at any time point (Fig. S2). This indicates that PFM type did not directly influence chlorophyll synthesis, despite the observed treatment-driven differences in soil moisture and temperature. Although these microclimate parameters can indirectly affect chlorophyll production, the absence of a treatment effect here is consistent with the view that plant N cycling dynamics are a more proximal determinant of chlorophyll status[56]. These findings contrast with those of Ashrafuzzaman et al.[57], who reported significant effects of transparent, blue and black PFMs on chlorophyll a and b, and total chlorophyll content in chili, with the highest values recorded under black PFM and the lowest under bare soil. Similarly, Panchal et al.[58] reported significant PFM effects on total chlorophyll content in chili, with black PFM producing the greatest values. The discrepancy between these studies and the present findings may reflect differences in climatic conditions, soil type, crop cultivar or the duration of PFM application.

All three PFM treatments significantly increased plant total P relative to the control in growing season 1 (Table 2), indicating that mulching enhanced P uptake, most likely through improved soil moisture retention and a more favorable root-zone microclimate. In growing season 2, the highest plant total P content was recorded under BDM. With respect to plant total N, both $LDPE_{black}$ and BDM significantly elevated total N concentrations relative to the control in growing season 1. In growing season 2, BDM again supported the highest plant total N concentration, indicating a capacity to promote N uptake over successive growing seasons. Plant total C was not significantly affected by PFM treatment in either season (Table 2).

Although the effects of PFM type on plant total P and N varied between seasons, BDM consistently enhanced the uptake of both nutrients in both growing seasons. This highlights the influence of PFM type on plant nutrient status and underscores the importance of regionally informed PFM selection for optimizing crop nutritional performance.

Table 2 Plant total carbon, nitrogen and phosphorus content in chili under control (CON), $LDPE_{ref}$, $LDPE_{black}$, and BDM treatments in growing seasons 1 and 2

Growing season	Treatment	Total C (%)	Total N (%)	Total P (%)
1	CON	38.5 ± 0.55a	2.19 ± 0.11b	0.32 ± 0.02b
	$LDPE_{ref}$	37.7 ± 1.41a	2.04 ± 0.01b	0.42 ± 0.02a
	$LDPE_{black}$	38.1 ± 0.71a	2.45 ± 0.17a	0.39 ± 0.02a
	BDM	37.8 ± 0.73a	2.51 ± 0.15a	0.42 ± 0.02a
2	CON	38.3 ± 0.94a	2.22 ± 0.11bc	0.47 ± 0.01b
	$LDPE_{ref}$	38.8 ± 1.49a	2.07 ± 0.01c	0.41 ± 0.02c
	$LDPE_{black}$	38.5 ± 0.95a	2.53 ± 0.17b	0.47 ± 0.02b
	BDM	40.4 ± 0.67a	2.87 ± 0.20a	0.55 ± 0.02a

Note: Within each growing season, means followed by the same letter are not significantly different (Tukey's test, $p \leqslant 0.05$). Values are mean ± SD ($n = 4$).

3.3.2 Impact of PFMs on crop biomass and yield

Control plots had significantly lower fresh and dry biomass, and yield than all PFM treatments in both growing seasons (Fig. 7), consistent with the greater exposure of unmulched soil to weed competition, evaporative moisture loss, temperature changes and reduced nutrient availability. In growing season 1, BDM and $LDPE_{ref}$ produced the highest fresh and dry biomass, and yield across all treatments (Fig. 7). In growing season 2, $LDPE_{ref}$ generated significantly higher fresh biomass and yield, whereas $LDPE_{black}$ and BDM performed similarly (Fig. 7(a,c)). The superior biomass production under $LDPE_{ref}$ is likely attributable to its capacity to moderate soil temperature under tropical conditions and suppress weed growth[59], thereby reducing competition for water and nutrients during the critical reproductive phase.

Yield across all PFM treatments was significantly greater than that of the control. The highest seasonal yields were recorded under BDM in growing season 1 and $LDPE_{ref}$ in growing season 2, at about 420 and 410 g·plant^{-1}, respectively. When extrapolated to a commercial planting density of 50000 plants·ha^{-1}, these values correspond to an estimated yield of about 21 t·ha^{-1}. This falls within the reported commercial yield range for cv. MICH HY 01 in Sri Lanka (12–24 t·ha^{-1} over a full 5-month growing cycle)[4], and is particularly notable given that the experimental growing period in this study spanned only 3 months. These results indicate that the use of PFMs, particularly BDM and $LDPE_{ref}$, can support yields consistent with high-performing commercial systems in the dry zone of Sri Lanka.

These findings are broadly consistent with the literature. Plastic mulching has been reported to enhance crop yield by 20%–50% relative to unmulched soil[60], through its combined effects on soil N conservation, temperature regulation, and reduction of soil water evaporation[61,62]. Gao et al.[63] similarly reported significantly higher yields of cotton, maize, potato and wheat under PFM compared to unmulched controls. PFM color has also been shown to influence yield outcomes, with black PFMs typically producing higher yields than transparent films, attributed to greater light absorption, weed suppression, and water retention[32, 59]. Sekara et al.[64] reported significantly higher tomato yields under both LDPE and BDMs compared to a no mulch treatment in a greenhouse experiment, and Samphire et al.[46] attributed yield improvements under BDMs to enhanced soil hydrothermal conditions, increased N use efficiency, and effective weed suppression.

The present results support BDM as a viable agronomic alternative to standard LDPE films in terms of crop biomass and yield. However, the relative decline in BDM performance between seasons may reflect progressive physical degradation of the film, which could reduce its capacity to retain soil moisture and nutrients over the course of the growing season. In contrast, the consistently strong performance of $LDPE_{ref}$ in both seasons is likely attributable to the structural integrity of the film throughout the growing period, which sustained effective nutrient conservation and minimized leaching losses.

4 Conclusions

This study provides a field-based evaluation of the effects of

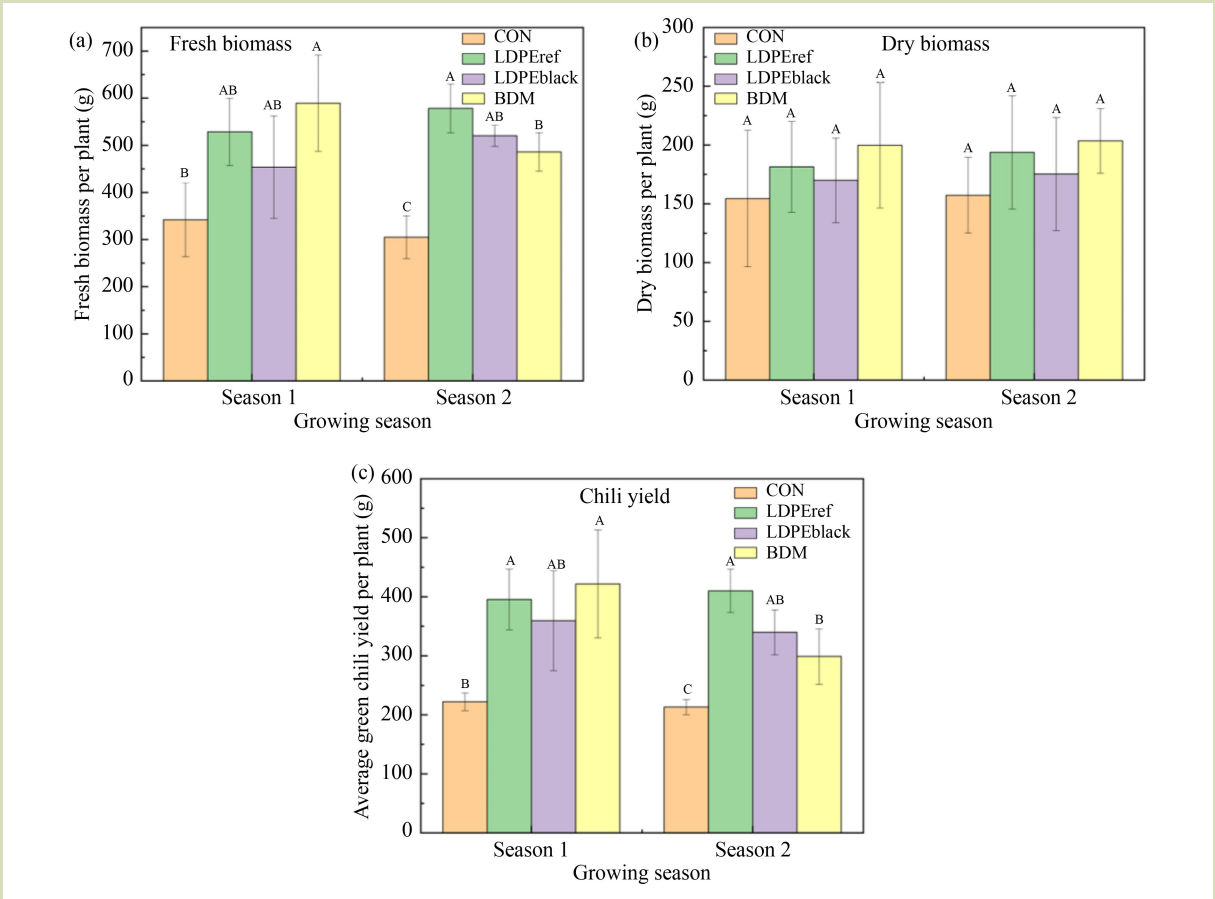


Fig. 7 (a) Plant fresh biomass, (b) plant dry biomass, and (c) chili (*Capsicum annuum*) yield under control (CON), reflective low-density polyethylene ($LDPE_{ref}$), black low-density polyethylene ($LDPE_{black}$), and black biodegradable PLA-PBAT (BDM) treatments in growing seasons 1 and 2. Values are mean ± SD (n = 4). Within each growing season, means with the same letter are not significantly different (Tukey's test, $p \leqslant 0.05$).

different PFM types on soil physicochemical properties and crop performance in the dry zone of Sri Lanka, a region where PFMs are widely used but remain poorly studied. Our first hypothesis that PFM application would alter soil physicochemical properties and improve crop performance relative to the control was partially supported. PFM application did not significantly affect soil pH, EC, bulk density or total C, indicating that short-term mulching does not fundamentally alter basic soil chemistry in tropical Alfisols. However, PFMs had a significant and treatment-dependent influence on soil microclimate and nutrient dynamics. $LDPE_{ref}$ and $LDPE_{black}$ consistently enhanced soil available P, $LDPE_{ref}$ improved NH_4^+ retention and all PFM treatments supported greater NO_3^- availability than the control, particularly under the wetter conditions of growing season 2 where leaching risk was greatest. $LDPE_{ref}$ and BDM were the most effective treatments for moderating soil temperature and moisture in both seasons, respectively. Leaf chlorophyll content was unaffected by PFM treatment, indicating that the observed microclimate modifications did not translate into measurable differences in plant photosynthetic capacity under the conditions of this study.

Our second hypothesis that standard LDPE PFMs would outperform BDM due to faster physical fragmentation was also partially supported. BDM delivered the highest fresh and dry biomass and yield in growing season 1 (about 420 g per plant, equivalent to about 21 $t \cdot ha^{-1}$), and enhanced plant total P and N uptake in both seasons, demonstrating clear agronomic potential. However, BDM performance declined relative to

$LDPE_{ref}$ in growing season 2, consistent with progressive film degradation reducing its capacity to retain soil moisture and nutrients over successive cropping cycles. $LDPE_{ref}$ maintained consistently strong agronomic performance in both seasons, supporting the highest yield in growing season 2 and emerging as the most stable and effective PFM type under the variable conditions of this study.

The long-term environmental implications of continued LDPE and BDM use, including plastic fragment accumulation, microplastic loading, and associated impacts on soil health and microbial communities, remain insufficiently understood and warrant dedicated investigation. BDM represents a promising alternative to standard LDPE films, but its durability, degradation kinetics and agronomic consistency under tropical field conditions require further assessment across multiple seasons. By providing empirical evidence from an agroecologically important but underrepresented region, this research addresses a critical knowledge gap and highlights the need for long-term field monitoring and life-cycle assessments to guide sustainable and regionally appropriate PFM use in Sri Lanka's intensifying agricultural systems.

Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-2026707 contains supplementary materials (Figs. S1–S2).

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Compliance with ethics guidelines

Achini Dias, Martine Graf, Meththa Gimhani, Mojith Ariyaratne, Anurudda Karunarathna, Chamila Perera, Davey L. Jones, David R. Chadwick, and Surani Chathurika declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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