technologies

MDPI

Article

Resource-Efficient Strip-Mulching Technology for Melon Production in Arid Uzbekistan: Polymer Input, Irrigation Water Savings, Yield, and Economic Assessment

Xamidulla Amirov [1,*], Shavkat Mamasov [1], Safar Sadinov [1], Xursheda Raxmonova [1], Sherzod Aliboyev [1], Abdubakir Kushbokov [1], Munira Kubayeva [2], Ilhom Rasulov [3], Javakhir Ergashev [3], Ilhom Nurillayev [4] and Surayyo Toshpulatova [4]

[1] Department of Smart Agrotechnologies, Institute of Agrobiotechnologies and Food Security, Samarkand State University named after Sharof Rashidov, 15 University Boulevard, Samarkand 140104, Uzbekistan; mamasovshavkat1963@gmail.com (S.M.); sadinovsafar@gmail.com (S.S.); rakhmonovaxursheda@gmail.com (X.R.); sherzodaliboyev3@gmail.com (S.A.); qabdubakir@mail.ru (A.K.)
[2] Department of Agroecosystem Management, Samarkand State University named after Sharof Rashidov, 15 University Boulevard, Samarkand 140104, Uzbekistan; munirakubayeva@gmail.com
[3] Department of Crop Production Systems, Institute of Agrobiotechnologies and Food Security, Samarkand State University named after Sharof Rashidov, 15 University Boulevard, Samarkand 140104, Uzbekistan; rasulovilhom1959@gmail.com (I.R.); javoxirergashev1895@gmail.com (J.E.)
[4] Department of Ecology, Green Transformation and Agrochemistry, Karshi State University, 17 Kuchabog Street, Karshi 180119, Uzbekistan; mr.ilhomnurillayev@gmail.com (I.N.); toshpulatovasurayyo97@gmail.com (S.T.)
* Correspondence: amirovxamidulla1976@gmail.com

Abstract

Polyethylene film mulching improves crop productivity in arid regions, but conventional full-surface use increases plastic input and post-season waste. This three-year field study evaluated localized strip mulching for drip-irrigated melon (*Cucumis melo* L.) in Samarkand, Uzbekistan. A randomized complete block design included three cultivars, bare soil, transparent film, and black film, with four blocks annually (2022–2024). Each 49.0 m^2 plot had an individual water meter. Mixed-effects analysis indicated strong mulch effects on marketable yield, seasonal irrigation, and irrigation water productivity (IWP) (all $p < 0.001$). Strip mulch covered 42.9% of the field and required 118.3 kg ha^{-1} film, 57.1% below the calculated full-surface material requirement. Relative to bare soil, transparent and black film increased the mean marketable yield by 11.4% and 16.9% and reduced measured seasonal irrigation by 14.1% and 18.5%, respectively; plot-level mean IWP increased by 29.7% and 43.4%. Black-film mulch use efficiency reached 38.04–42.27 kg additional fruit kg^{-1} film. Ko'kcha-588 with black film produced 35.0 t ha^{-1} with 3845.8 m^3 ha^{-1} irrigation and 9.10 kg m^{-3} mean plot-level IWP. At the base price scenario, black film provided an incremental margin of 3.67 million UZS ha^{-1} before additional labor and end-of-life costs. The estimated 295 kg CO_2-eq ha^{-1} reduction concerns virgin-LDPE resin production only. Yield and irrigation comparisons refer to bare soil; the full-surface comparison concerns calculated material input. Additional field monitoring showed stronger soil warming under transparent film and lower uncovered inter-row weed biomass with black film; these observations do not establish the independent mechanism of the yield response.

Academic Editor: Xinqing Xiao

Received: 30 September 2026
Revised: 2 November 2026
Accepted: 3 November 2026
Published: 12 November 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

Keywords: agricultural plastic waste; arid agriculture; *Cucumis melo* L.; drip irrigation; irrigation water productivity; material efficiency; polyethylene film

1. Introduction

Plastic-film mulching remains one of the most effective field practices for modifying the soil hydrothermal environment in vegetable and field crops. By limiting direct evaporation, moderating soil temperature, suppressing weeds, and protecting the wetted root zone, polyethylene mulch can improve yield and water-use performance, particularly where evaporative demand is high [1–3]. The same technology, however, has a material efficiency problem: conventional application can require large quantities of polymer every season, followed by labor-intensive recovery and disposal. Incomplete collection leaves fragments in agricultural soils, where weathering and mechanical disturbance contribute to the formation of microplastics and nanoplastics [4–7]. Recent assessments, therefore, increasingly treat agricultural mulch not only as an agronomic input but also as a material flow that should be minimized, recovered, or replaced where technically feasible [7,8].

Water scarcity gives this material-use problem an additional engineering dimension. Mulches alter the soil surface energy and water balance, and the magnitude of the effect depends on the fraction of soil covered, film optical properties, crop development stage, irrigation regime, and climate [2,9]. Reviews of drip irrigation under plastic mulch show that the combination can substantially improve water productivity, but reported responses are strongly system-specific [10]. In melon, irrigation thresholds and irrigation amount directly affect marketable yield and fruit quality [11–13]. Consequently, a field technology intended for arid melon production should be evaluated against two resources simultaneously: polymer input and measured irrigation input. Work on geometry-optimized strip tillage in semi-arid vineyards has documented infiltration and soil-structure responses [14]; the corresponding engineering design considerations have been surveyed for water-limited seedbeds [15]. Research on local soil loosening and soybean productivity [16] addresses a different intervention but illustrates how localized management may affect crop response. These studies do not quantify the film color effects investigated here.

Film color is also consequential. Transparent polyethylene transmits short-wave radiation and can warm the upper soil layer strongly, whereas black film absorbs and blocks most photosynthetically active radiation, thereby suppressing weeds and altering the thermal regime [1,2]. Melon responses reported in the literature are not uniform. Under temperate or cooler conditions, transparent film can be beneficial because additional soil warming is favorable [17–20]. Under hot and arid conditions, the same optical behavior may increase thermal stress or support weed growth beneath the film, while black mulch may provide a more stable root-zone environment. These contrasting responses make field testing in the target climate necessary rather than assuming that one film color is universally superior. Related experiments in hot–arid squash melon [21] and drip-irrigated watermelon under black and transparent films [22] illustrate the importance of crop and climate when comparing cover treatments. In muskmelon, mulch and fertigation have also been linked to fruit quality responses [23], a response that was not measured in this field experiment.

A second route for reducing the environmental burden of mulching is material substitution. Biodegradable mulch films have produced competitive yields in melon and other horticultural crops in several field studies [24–26], and comparative studies in maize have demonstrated that agronomic performance can approach that of polyethylene under suitable conditions [27]. Life-cycle assessments, nevertheless, show that environmental

performance depends on polymer formulation, thickness, manufacturing, and end-of-life pathway [28]. Recycling conventional polyethylene is also possible, but agricultural film is frequently contaminated with soil and organic matter, which increases collection and processing costs [29]. Where residues remain in soil, their fragmentation can also affect soil biota and key soil functions [30,31]. These constraints make source reduction an important complementary strategy: if the agronomic function can be maintained with less film, the amount requiring purchase, transport, collection, and end-of-life management decreases at the beginning of the waste hierarchy rather than after waste has already been generated.

Partial plastic coverage in melon production has already been examined experimentally. Greenhouse studies compared full, row-only and uncovered soil surfaces together with irrigation thresholds or drip-line density [32,33]. These results provide a relevant design precedent, but their greenhouse conditions and treatment combinations do not establish the three-year field performance of the particular 42.9% strip geometry, two polyethylene film colors, and plot-metered irrigation evaluated here.

Strip mulching concentrates polymer in the crop-row corridor. Previous melon studies have examined film type, irrigation management, yield, and fruit quality [11–13,17–20,24–26], but these findings do not establish the combined performance of the present 42.9% coverage geometry under Samarkand field conditions. The specific gap addressed here is the joint quantification of plot-metered irrigation, marketable yield, and polymer demand within one three-year factorial experiment. Linking these measurements to film-use indicators and explicit price scenarios allows the agronomic response to be assessed alongside material requirements. The contribution is this integrated field assessment, rather than the invention of plastic mulching itself.

The aim of this study was, therefore, to evaluate a resource-efficient strip-mulching technology based on localized polyethylene application for melon production under arid, drip-irrigated conditions in Uzbekistan. This study tested transparent and black 30 μm polyethylene films across three cultivars over three seasons using a randomized complete block design with plot-level irrigation metering. The field hypothesis was that strip mulch would increase marketable yield and reduce applied irrigation relative to bare soil, with cultivar-dependent responses. Polymer reduction was calculated separately against a 100% coverage benchmark; agronomic equivalence to full-surface mulching was not tested.

2. Materials and Methods

2.1. Experimental Site, Soil, and Crop Management

Field experiments were conducted in 2022, 2023, and 2024 at the experimental production site of the ‘Ishonch’ farm, the Nurabad district, the Samarkand region, Uzbekistan (39°34′10″ N, 66°20′39″ E). The soil was described locally as a newly irrigated light sierozem; “light” denotes the local soil classification, whereas “heavy loamy” describes its texture. A diagnostic profile sufficient for formal WRB or USDA classification was not available. In the 0–30 cm layer, the humus content ranged from 0.85% to 0.98%, the field capacity (FC) was 21.4% on a dry-mass basis, and the bulk density was 1.34 g cm^{-3}. The regional production environment is characterized by high evaporative demand and limited irrigation resources, conditions under which drip irrigation is increasingly used to improve water-use efficiency [34]. Three regionally released melon cultivars were included: Ko‘k kalla push (early), Mahalliy Samarqand obi novvoti (mid-season), and Ko‘kcha-588 (mid-late). An independent Samarkand-region maize study reported soil physical and crop responses under contrasting minimum-tillage management [35]; its results provide regional context only, not baseline measurements for the present plots.

Fertilization and plant protection practices were common to all plots, while weed control differed according to soil cover. Fertilizer was applied at N 180, P 120, and K 100 kg ha^{-1} of active ingredient; 50% of N and 100% of P and K were applied before ploughing, and the remaining 50% of N was divided between two in-season top dressings. Two to three inter-row loosenings were performed before canopy closure. Weeds were removed manually in the bare-soil control, while the film provided the principal physical weed suppression function in mulched plots. Plant protection treatments and harvest operations were the same across treatments. Fertilizer system trials with white cabbage [36] have likewise documented crop and soil responses to nutrient management; those observations are cited only to explain the importance of keeping fertilization common across the melon treatments.

Additional baseline soil pH, organic carbon, and available nutrient measurements and irrigation water chemistry were unavailable. Regional weather was characterized using observed monthly station records rather than assumed plot-level meteorological measurements. Accordingly, weather variation is described at the station scale; causal attribution of year-to-year treatment differences to specific weather events requires further analysis.

Sowing was performed on 18 April 2022, 16 April 2023, and 20 April 2024, and the final harvests were completed on 20 August 2022, 18 August 2023, and 22 August 2024, respectively. Each sowing-to-final-harvest interval was 124 days. These dates applied to the experimental cultivars. The monthly meteorological series for April–August 2022–2024 was obtained from the Japan Meteorological Agency (JMA) ClimatView archive for Samarkand Station 38696 (39.63° N, 66.95° E; elevation: 724 m). The archived parameters comprise mean air temperature, mean daily maximum and minimum air temperature, and monthly precipitation. The April–August sums were 135 mm in 2022, 45 mm in 2023, and 114 mm in 2024. These are complete-calendar-month totals, not rainfall accumulated strictly between sowing and final harvest. The source station is a regional meteorological reference, not an on-plot weather logger (see Table S6).

2.2. Experimental Design and Plot Geometry

The experiment followed a randomized complete block design (RCBD), with four blocks in each year. Within every block, the full factorial combination of three cultivars and three soil cover treatments was represented once, giving nine plots per block and 36 plots per year. The same field and four physical blocks were retained, and the nine treatment combinations were independently re-randomized within each block in each year. The dataset comprises 36 plots per season and 108 plot-year observations, rather than 108 simultaneously independent physical plots. Annual re-randomization reduces confounding with previous treatment allocation but does not by itself exclude carry-over effects.

Each plot was 3.50 m wide and 14.0 m long (49.0 m^2). The planting pattern was paired-row, (2.80 + 0.70) × 0.70 m: 2.80 m between adjacent row pairs, 0.70 m between rows within a pair, and 0.70 m between plants along the row. Each plot contained two rows with 20 plants per row, giving 40 plants and a nominal feeding area of 1.225 m^2 $plant^{-1}$. Marketable yield was determined from all 40 plants in the plot.

2.3. Strip-Mulching Technology and Polymer Input

Three soil cover treatments were evaluated: (i) the control, bare soil without film; (ii) transparent polyethylene film, 30 μm thick; and (iii) black polyethylene film, 30 μm thick. Smooth film supplied with a 1.50 m width was divided into two 0.75 m strips and laid along the two plant rows, together forming the 1.50 m covered corridor. In the repeating 3.50 m field module, the two strips occupied 1.50 m, corresponding to 42.9% surface

coverage (Figure 1). One drip line per pair of rows was positioned centrally between the rows, beneath the film. The uncovered interval between adjacent covered corridors was 2.00 m.

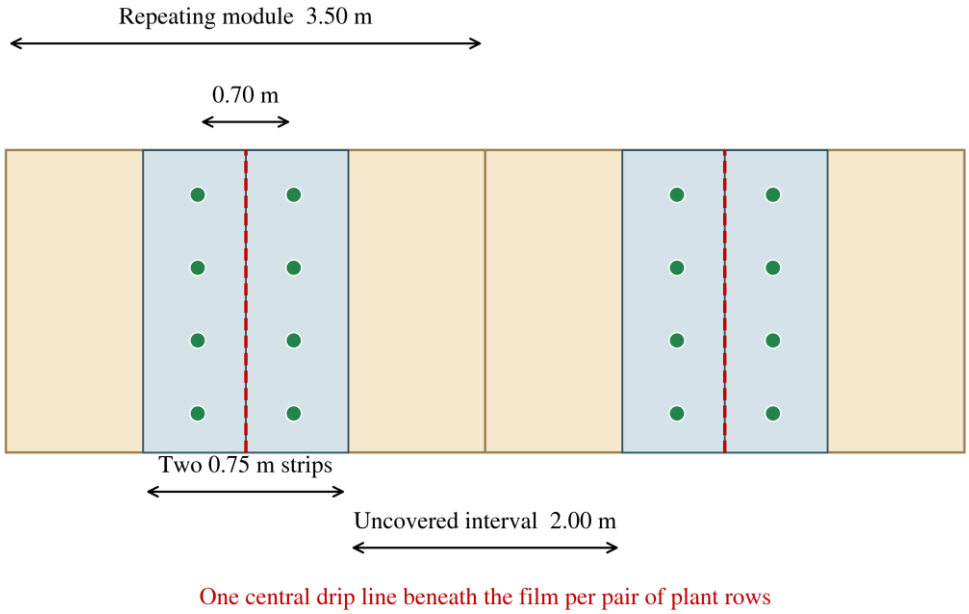


Figure 1. Schematic of the strip-mulching technology: arrangement of film strips, drip irrigation lines and plant rows within the repeating field module. Each 3.50 m module contains two 0.75 m film strips and one central drip line beneath the film, between plant rows spaced 0.70 m apart. The red dashed line identifies the drip line; green symbols identify plants. Diagram not to longitudinal scale.

The strip geometry and the associated polymer demand were calculated directly from the repeating 3.50 m field module. The relations used to determine fractional coverage, film-covered area, total strip length, and polymer mass are combined in Equation (1):

$$C_f = \frac{n_s b_s}{B_m}, \qquad A_f = A_h C_f, \qquad L_s = \frac{A_f}{b_s} = \frac{A_h n_s}{B_m}, \qquad M_f = \rho_f \delta_f A_f = \rho_f \delta_f A_h \frac{n_s b_s}{B_m} \tag{1}$$

In Equation (1), C_f is the fractional surface coverage; $n_s = 2$ is the number of strips per module; $b_s = 0.75$ m is the strip width; $B_m = 3.50$ m is the module width; $A_h = 10{,}000$ m² is one hectare; A_f is the covered area (m² ha⁻¹); L_s is the total strip length (m ha⁻¹); $\rho_f = 920$ kg m⁻³ is the polyethylene density; $\delta_f = 30 \times 10^{-6}$ m is the film thickness; and M_f is the film input (kg ha⁻¹).

The full-surface material benchmark and the absolute and relative polymer savings were calculated using Equation (2):

$$M_{100} = \rho_f \delta_f A_h, \qquad \Delta M_f = M_{100} - M_f = M_{100}\left(1 - C_f\right), \qquad R_M = 100\frac{\Delta M_f}{M_{100}} = 100\left(1 - C_f\right) \tag{2}$$

In Equation (2), M_{100} is the calculated film requirement for 100% coverage (kg ha⁻¹), ΔM_f is the avoided polymer input (kg ha⁻¹), and R_M is the relative reduction (%). This is a comparison of material requirements at equal film thickness and density, not a measured comparison of the yields or water demands of strip and full-surface mulching.

For 30 µm polyethylene at a density of 0.92 g cm⁻³, the film mass was 27.6 g m⁻². The strip configuration covered 4286 m² ha⁻¹, equivalent to 5714 m of a 0.75 m wide strip per

hectare, and required 118.3 kg film ha^{-1}. A 100%-surface-coverage material benchmark at the same film thickness would require 276.0 kg ha^{-1}. The strip configuration, therefore, reduced polymer input by 157.7 kg ha^{-1}, or 57.1%, relative to that calculated material requirement. Film strips and drip lines were installed manually, and the film was removed manually after the season. The recovered film mass, residual film in soil, and final recycling or disposal route were not quantified. Potential routes to mechanization include combined strip preparation and film-laying implements [37–39] and manually operated mulch/drip-laying equipment [40]. Studies of flexible working elements [41], flat-blade geometry [42], and rotary cultivator points [43] provide further design context. These publications concern machinery development rather than additional field treatments in the present study.

2.4. Irrigation Control, Flow Measurement, and Irrigation Water Productivity

Drip irrigation was scheduled based on soil moisture deficit in the 0–50 cm layer, using a pre-irrigation threshold of 75–80% of field capacity (FC) for all treatments. Soil samples were collected before irrigation, and gravimetric water content was determined by oven drying at 105 °C to constant mass, following GOST 28268-89 [44]. Irrigation was initiated when the threshold was reached. The target application was calculated from the deficit to FC in the controlled layer, and water delivery was stopped after the calculated volume had been supplied. The same threshold-based procedure was applied to mulched and control plots; a common seasonal irrigation total was not imposed.

Irrigation water volume was measured separately for each plot using a Baylan KK-12 single-jet dry-type water meter (DN15, metrological class B; R = 100) at the inlet of the plot's drip line. R denotes the ratio Q_3/Q_1, not a percentage error. Readings before and after each irrigation event were differenced, summed over the season, and converted to m^3 ha^{-1} using the 49.0 m^2 plot area. For example, 22.05 m^3 per plot corresponds to 4500 m^3 ha^{-1}.

A conditional ±2%-indication-error scenario was used for sensitivity analysis only. It was not treated as a verified accuracy specification for the installed meters, the register resolution, or the standard deviation of paired treatment differences. Experimental studies of mechanical water meters have documented changes in indication error with operating flow and pressure [45], while field calibration research emphasizes the distinction between traceable measurement uncertainty and nominal accuracy specifications [46]. Installation-specific calibration results and operating-flow records were unavailable. The conditional ±2% sensitivity scenario, therefore, does not establish the field uncertainty for each irrigation event.

The pre-irrigation threshold was represented in gravimetric form by Equation (3):

$$w_{thr} = k_{FC} w_{FC}, \qquad 0.75 \le k_{FC} \le 0.80 \tag{3}$$

In Equation (3), w_{thr} is the threshold gravimetric water content (kg kg^{-1}), w_{FC} = 0.214 kg kg^{-1} is the water content at FC, and k_{FC} is the adopted fraction of FC (0.75–0.80). Water contents entered into Equations (3) and (4) are mass fractions, not percentages.

The equivalent root-zone water deficit corresponding to the threshold can be expressed as an irrigation depth using Equation (4):

$$d_i = 10^3 \frac{\rho_b}{\rho_w} Z_r \left(w_{FC} - w_i \right) = 10^3 \frac{\rho_b}{\rho_w} Z_r w_{FC} \left(1 - k_{FC} \right) \tag{4}$$

In Equation (4), d_i is the root-zone deficit (mm), ρ_b and ρ_w are the soil bulk density and water density in the same units, Z_r = 0.50 m is the controlled depth, and w_i is the measured pre-irrigation gravimetric water content. The final equality applies when w_i

equals the adopted threshold. The measured FC and bulk density characterize the reported 0–30 cm layer; their use over 0–50 cm is a scheduling approximation. Seasonal totals were obtained from the meters, not by summing calculated deficits.

Measured seasonal irrigation for each plot was converted to a hectare basis from the accumulated meter-reading differences using Equation (5):

$$I_p = \frac{A_h}{A_p} \sum_{j=1}^{N_i} \left(V_{j,\text{after}} - V_{j,\text{before}} \right) \quad (5)$$

In Equation (5), I_p is the seasonal irrigation for plot p (m³ ha⁻¹), A_p = 49.0 m² is the plot area, N_i is the number of irrigation events, and $V_{j,\text{after}}$ and $V_{j,\text{before}}$ are the meter readings (m³) bracketing event j.

Marketable yield and irrigation water productivity (IWP, kg m⁻³) were calculated at the plot level from harvested mass and metered irrigation using Equation (6):

$$Y_p = \frac{10 W_p}{A_p}, \qquad \text{IWP}_p = \frac{10^3 Y_p}{I_p} = \frac{10^4 W_p}{A_p I_p} \quad (6)$$

In Equation (6), W_p is the cumulative marketable fruit mass (kg plot⁻¹), Y_p is the marketable yield (t ha⁻¹), I_p is the seasonal irrigation (m³ ha⁻¹), and IWP_p is the irrigation water productivity (kg m⁻³). The IWP was calculated for each plot before averaging; it is not generally equal to the ratio of treatment-level mean yield and mean irrigation.

2.5. Yield, Soil Temperature, Weed Biomass, and Material Efficiency Indicators

Melons were harvested manually in three to four pickings as fruits reached marketable maturity. Fruit mass from all 40 plants was independently recorded for each plot in grams and accumulated over the complete harvest period; these primary weights were converted to kilograms and then to t ha⁻¹, so the response was seasonal yield rather than yield per picking. Marketable fruits had a greatest transverse diameter of at least 10 cm for Ko'k kalla push and at least 15 cm for Mahalliy Samarqand obi novvoti and Ko'kcha-588, following the size thresholds in GOST 7178-85 [47]. Diseased, pest-damaged, cracked, malformed, sunburned, underripe, overripe, and undersized fruits were excluded. The same criteria were applied across mulch treatments. Soluble solids, firmness, and treatment-level fruit size distributions were not measured. Conversion to t ha⁻¹ followed Equation (6).

Soil temperature was measured in situ using a PTET-62 electric thermometer with remote sensors (reported instrumental accuracy of ±0.1 °C) at depths of 5, 10, and 20 cm. Sensors were placed beneath the film in mulched treatments and at corresponding exposed-soil positions in the bare-soil control. The observation dates were 16 May and 10 June 2022, 15 May and 9 June 2023, and 14 May and 8 June 2024, covering emergence to early flowering. Readings were obtained at 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, 21:00, and 00:00 on each observation date. For each mulch × depth × year group, observations covered three cultivars, four blocks and two dates (3 × 4 × 2 × 8 = 192 raw readings). The eight readings for each cultivar × block × date were averaged to produce 24 daily-mean values per group and year. Annual means and sample SDs were calculated over these 24 daily means; they describe between-cultivar, between-block and between-date dispersion, not within-day variability. The summary across 2022–2024 uses the three annual treatment means and their sample SDs. These repeated observations are not 24 independent randomized blocks; no inferential p-values are assigned to the soil temperature contrasts.

Weed aboveground biomass was sampled on 25 June 2024, 30 days after the last control-treatment weeding, using a 0.25 m² quadrat (0.5 m × 0.5 m) placed in the 2.00 m

wide open bare-soil strip between adjacent film-covered corridors. In bare-soil control plots, the corresponding inter-row position was sampled. One quadrat was evaluated per block and treatment (n = 4 blocks). Fresh weed samples were oven-dried at 65 °C to constant mass and weighed; quadrat dry mass was multiplied by four to express biomass in g m^{-2}. Means and sample SDs were calculated from the four block values. The measurements characterize weed biomass in comparable uncovered strips only; vegetation under the film was not sampled, and total field-area weed biomass cannot be inferred from these quadrats.

Mulch use efficiency (MUE, kg fruit kg^{-1} film) and plastic intensity (PI, kg film t^{-1} fruit) were used as complementary material efficiency indicators and calculated using Equation (7):

$$\mathrm{MUE} = \frac{10^3\left(Y_t - Y_c\right)}{M_f} = \frac{10^3 \Delta Y}{M_f}, \qquad \mathrm{PI} = \frac{M_f}{Y_t} \tag{7}$$

In Equation (7), Y_t and Y_c are the three-year mean yields of a mulched treatment and its cultivar control, $\Delta Y = Y_t - Y_c$ (t ha^{-1}), and M_f = 118.3 kg ha^{-1} is the strip-film input. MUE is expressed as kg additional fruit kg^{-1} film and PI as kg film t^{-1} fruit. Equation (2) quantifies avoided film input, not measured recovered waste or soil residues.

2.6. Screening Environmental and Economic Assessment

A screening estimate of virgin-LDPE resin production greenhouse gas emissions used 1.87 kg CO_2-eq kg^{-1} LDPE, the PlasticsEurope resin benchmark cited by Zeilerbauer et al. [48]. That source accounts for film extrusion separately. The present estimate, therefore, covers resin production only, excludes film conversion, and is not a complete film production footprint or life-cycle assessment. It quantifies a potential upstream consequence of lower polymer input rather than measured environmental effects at the field site.

The corresponding polymer production screening calculation is given in Equation (8):

$$E_{\mathrm{strip}} = EF_{\mathrm{LDPE}} M_f, \qquad E_{100} = EF_{\mathrm{LDPE}} M_{100}, \qquad \Delta E = EF_{\mathrm{LDPE}}\left(M_{100} - M_f\right) = EF_{\mathrm{LDPE}} \Delta M_f \tag{8}$$

In Equation (8), EF_{LDPE} = 1.87 kg CO_2-eq kg^{-1} is the virgin-resin production factor; E_{strip} and E_{100} are the corresponding burdens for strip and theoretical full coverage; and ΔE is their difference (kg CO_2-eq ha^{-1}). Extrusion, transport, installation, removal, cleaning, recycling, disposal, and irrigation energy are outside this boundary. The factor is a literature benchmark rather than a local manufacturing inventory.

Economic calculations used a base melon price of 1.5 million UZS t^{-1}, a common production cost allowance excluding film of 18.0 million UZS ha^{-1}, and film prices of 23,000–35,000 UZS kg^{-1} (base scenario: 29,000 UZS kg^{-1}). These are scenario assumptions applied to the 2022–2024 yield results, not a verified time series of farm transactions. The strip-film purchase cost was 2.72–4.14 million UZS ha^{-1}; the calculated full-coverage equivalent was 6.35–9.66 million UZS ha^{-1}. Additional labor for installation and removal, irrigation labor, recovery, and disposal were not separately costed. Water-charge and pumping-energy savings were not monetized. The resulting net-income and profitability indicators are, therefore, partial-budget estimates. Table S3 consolidates the assumptions and exclusions.

The economic accounting relations are summarized in Equation (9):

$$G = P_y Y, \qquad C_{\mathrm{tot}} = C_0 + P_f M_f, \qquad NI = G - C_{\mathrm{tot}}, \qquad \Pi = 100\frac{NI}{C_{\mathrm{tot}}} \tag{9}$$

In Equation (9), P_y is the melon price (UZS t^{-1}), P_f is the film price (UZS kg^{-1}), C_0 is the common production cost allowance (UZS ha^{-1}), G is the gross revenue, C_{tot} is the included total cost, NI is the partial-budget net income (all UZS ha^{-1}), and Π is the profitability relative to the included cost (%).

For the treatment-to-control comparison, the incremental net income and the corresponding break-even quantities were calculated using Equation (10):

$$\Delta NI\left(P_y, P_f\right) = P_y\left(Y_t - Y_c\right) - P_f M_f, \qquad \Delta Y_{BE} = \frac{P_f M_f}{P_y}, \qquad P_{y,BE} = \frac{P_f M_f}{Y_t - Y_c} \tag{10}$$

In Equation (10), ΔNI is the incremental margin before uncosted operations, ΔY_{BE} is the yield increase required to cover film purchase (t ha^{-1}), and $P_{y,BE}$ is the corresponding break-even melon price (UZS t^{-1}). For an additional cost allowance C_{add} (UZS ha^{-1}), the adjusted margin is $\Delta NI - C_{add}$; any monetized irrigation saving would be added separately. This accounting sensitivity does not estimate unmeasured labor costs.

2.7. Statistical Analysis

Yield, seasonal irrigation water applied, and plot-level IWP were analyzed using linear mixed-effects models. For a generic response z, year, cultivar, mulch treatment, and all two- and three-way interactions were fitted as fixed effects, while block nested within year was included as a random intercept, as represented in Equation (11).

Year was treated as fixed because inference concerns the three observed seasons, not a well-sampled population of years. The primary model uses a block-within-year intercept; reuse of the four physical blocks was examined in a sensitivity model with both persistent-block and block-year intercepts. Only four persistent blocks are available, and boundary or Hessian warnings in that sensitivity fit preclude definitive claims about temporal variance components. The results are conditional on the supplied plot-year dataset.

$$z_{ybcm} = \mu + \alpha_y + \beta_c + \gamma_m + (\alpha\beta)_{yc} + (\alpha\gamma)_{ym} + (\beta\gamma)_{cm} + (\alpha\beta\gamma)_{ycm} + u_{b(y)} + \varepsilon_{ybcm} \tag{11}$$

The indices *y*, *b*, *c*, and *m* denote year, block within year, cultivar, and mulch treatment, respectively; α, β, γ, and their interaction terms are fixed effects. The block-within-year intercept was assumed to be normally distributed with variance σ_b^2, and the residual error was assumed to be normally distributed with variance σ_ε^2.

Marginal and conditional coefficients of determination were calculated from the fixed-effect prediction variance (σ_f^2), block-within-year variance (σ_b^2), and residual variance (σ_ε^2), according to Equation (12):

$$R_m^2 = \frac{\sigma_f^2}{\sigma_f^2 + \sigma_b^2 + \sigma_e^2}, \qquad R_c^2 = \frac{\sigma_f^2 + \sigma_b^2}{\sigma_f^2 + \sigma_b^2 + \sigma_e^2} \tag{12}$$

Fixed effects were evaluated using sum-to-zero coding and Wald χ^2 tests for effects averaged over the other factors, using the quadratic form in Equation (13):

$$\chi_W^2 = \left(\mathbf{L}\boldsymbol{\beta}\right)^T \left[\mathbf{L}\,\mathrm{Var}\left(\boldsymbol{\beta}\right)\mathbf{L}^T\right]^{-1} \left(\mathbf{L}\boldsymbol{\beta}\right), \qquad df = \mathrm{rank}\left(\mathbf{L}\right) \tag{13}$$

where *L* is the hypothesis contrast matrix, β is the estimated fixed-effect parameter vector, Var(β) is its covariance matrix, and the test degrees of freedom equal rank(*L*).

Estimated marginal means were averaged equally over the three years. Within each cultivar, transparent versus control, black versus control, and black versus transparent contrasts were calculated from the fixed-effect covariance matrix. Holm adjustment was

applied to the nine comparisons for each response; 95% confidence intervals are pointwise asymptotic intervals. Tables S1 and S2 provide the estimates and comparisons. These marginal hypotheses replace reference-level coefficient tests, which can answer a different question in a model containing interactions.

For direct technology comparisons, plot-matched differences between each mulched treatment and the corresponding control were calculated within cultivar × year × block combinations. The paired mean, dispersion, and 95% confidence interval were obtained using Equation (14):

$$\bar{d} = \frac{1}{n}\sum_{i=1}^{n} d_i, \qquad s_d = \sqrt{\frac{\sum_{i=1}^{n}\left(d_i - \bar{d}\right)^2}{n-1}}, \qquad CI_{95\%} = \bar{d} \pm t_{0.975,n-1}\frac{s_d}{\sqrt{n}} \tag{14}$$

In Equation (14), each paired difference is treatment minus its matched control, n = 36 contrasts were available per mulch treatment, the dispersion term is the standard deviation of those paired differences, and the confidence limit uses the two-sided Student's critical value with $n - 1$ degrees of freedom. These paired summaries describe the tabulated contrasts and do not model the persistent physical-block dependence. Their intervals quantify variation in the supplied values, not total measurement uncertainty; primary treatment inference uses the mixed model.

Relative effects were reported with a sign convention that makes agronomic improvement positive, as defined in Equation (15):

$$E_Y = 100\frac{Y_t - Y_c}{Y_c}, \qquad S_I = 100\frac{I_c - I_t}{I_c}, \qquad E_{\mathrm{IWP}} = 100\frac{\mathrm{IWP}_t - \mathrm{IWP}_c}{\mathrm{IWP}_c} \tag{15}$$

The three quantities in Equation (15) are relative yield increase, irrigation-water saving, and relative IWP increase. The reversed numerator for irrigation ensures that a reduction in water use is shown as a positive saving.

For model comparison, the Akaike information criterion was calculated using Equation (16):

$$AIC = 2k - 2\ln\mathcal{L}\left(\boldsymbol{\theta}\right) \tag{16}$$

In Equation (16), k is the number of estimated parameters, and $L(\theta)$ is the maximized likelihood. Models were fitted by maximum likelihood. Residual-versus-fitted and normal Q–Q plots were examined, and log-transformed irrigation was fitted as a sensitivity analysis. Shapiro–Wilk results are reported as supplementary residual diagnostics, not as proof that all model assumptions hold. The original calculations used Statistica 10.0 and Mathcad 15; the revised mixed-model verification used Python 3 with statsmodels 0.14.6, NumPy, and SciPy. A significance level of $p < 0.05$ was used.

Descriptive variability was calculated from Supplementary Data S1. For each mulch treatment, plot-level coefficients of variation were calculated from the 36 observations pooled across cultivars, years, and blocks, while temporal coefficients of variation were calculated from the three annual treatment means. Matched treatment-to-control contrasts were additionally summarized in original measurement units by their mean difference, standard deviation, standard error, 95% confidence interval, paired t-statistic, and two-sided p-value.

2.8. Generative AI-Assisted Manuscript Preparation

Gemini 2.5 Flash (developed by Google) was used during manuscript revision to assist with language editing. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

3. Results

3.1. Mixed-Model Effects on Yield, Irrigation, and IWP

The three-year marginal tests identified strong cultivar and mulch effects on marketable yield (both $p < 0.001$; Table 1). The cultivar × mulch interaction was significant ($\chi^2 = 103.22$; $p < 0.001$), confirming cultivar-dependent yield increments. The year main effect was significant ($\chi^2 = 16.85$; $p < 0.001$), whereas year × cultivar was not ($p = 0.180$). The year × mulch interaction was also significant ($\chi^2 = 17.88$; $p = 0.001$), indicating that changes in mulch response across seasons should be assessed rather than assuming perfectly parallel treatment responses. Tests refer to marginal effects under sum-to-zero coding.

Table 1. Wald χ^2 tests for fixed effects in linear mixed-effects models of marketable yield, seasonal irrigation water applied, and irrigation water productivity (IWP).

Effect	df	Yield χ^2	*p*	Irrigation χ^2	*p*	IWP χ^2	*p*
Year	2	16.85	<0.001	44.82	<0.001	100.02	<0.001
Cultivar	2	12,917.87	<0.001	3333.98	<0.001	3532.61	<0.001
Mulch	2	11,610.68	<0.001	70,249.48	<0.001	31,564.82	<0.001
Year × Cultivar	4	6.27	0.180	11.20	0.024	6.84	0.144
Year × Mulch	4	17.88	0.001	29.64	<0.001	10.37	0.035
Cultivar × Mulch	4	103.22	<0.001	0.39	0.984	70.35	<0.001
Year × Cultivar × Mulch	8	9.68	0.288	9.03	0.340	8.43	0.393

Note: Models use sum-to-zero coding, maximum-likelihood estimation, and a random block-within-year intercept. Effects are evaluated as model-based Wald χ^2 tests. $p < 0.001$ denotes significance below the reporting threshold; $p > 0.999$ denotes no detectable departure from the tested null, not proof of equality. $\chi^2 < 0.01$ represents a near-zero statistic, not a *p*-value. The reported statistics were calculated from Supplementary Data S1.

Seasonal irrigation showed significant effects of year, cultivar, and mulch (all $p < 0.001$; Table 1). Year × cultivar ($p = 0.024$) and year × mulch ($p < 0.001$) were significant, whereas cultivar × mulch was not ($p = 0.984$). For IWP, year, cultivar, and mulch main effects were significant (all $p < 0.001$), together with year × mulch ($p = 0.035$) and cultivar × mulch ($p < 0.001$); year × cultivar was not significant ($p = 0.144$). The direction of the film effects remained consistent across the observed cultivars and seasons, although their magnitude varied.

Variance components and goodness-of-fit statistics for the same mixed models are summarized in Table 2.

Table 2. Mixed-model variance components, goodness-of-fit indicators, and complementary variance diagnostics.

Response	Block SD	Residual SD	Marginal R^2	Conditional R^2	AIC	Block Share of Unexplained Variance, %	Residual CV, %
Marketable yield, t ha^{-1}	0.208	0.190	0.991	0.996	35.55	54.4	0.62
Seasonal irrigation, m^3 ha^{-1}	30.9	14.2	0.992	0.999	982.98	82.5	0.35
IWP, kg m^{-3}	0.055	0.064	0.995	0.997	-203.30	42.4	0.85

Note: SD = standard deviation. Marginal R^2 quantifies variance explained by fixed effects; conditional R^2 includes the block-within-year random intercept. "Block share of unexplained

variance" is $\frac{\sigma_\beta^2}{\sigma_\beta^2+\sigma_e^2}\times 100$. Residual CV is the residual SD divided by the overall response mean. AIC values refer to maximum-likelihood fits.

The conditional R^2 exceeded 0.99 for all three response models, but explained variance does not alone establish adequacy. The primary irrigation model assigned approximately 82.5% of the residual-plus-block variance to block-within-year, with a residual CV of 0.35% (Table 2). The irrigation residuals deviated from normality (Shapiro–Wilk $W = 0.885$; $p < 0.001$), and the log-irrigation fit did not remove this departure ($W = 0.878$; $p < 0.001$). Mulch and cultivar effects remained significant on the log scale; the year main effect was also significant ($p < 0.001$), whereas year × mulch was not ($p = 0.255$). IWP residuals also departed from normality ($W = 0.960$; $p = 0.0024$), qualifying interpretation of asymptotic Wald p-values. Supplementary Figure S1 and Table S4 show the updated residual and alternative block-covariance diagnostics. The persistent-block IWP fit produced a boundary warning.

3.2. Marketable Yield

Across cultivars, the marketable yield averaged 28.0 t ha^{-1} in the bare-soil control, 31.2 t ha^{-1} under transparent film, and 32.73 t ha^{-1} under black film. These values correspond to increases of 11.4% and 16.9%, respectively, from individual plot observations. Ko'kcha-588 with black film produced the highest three-year mean yield, 35.0 t ha^{-1}. The significant cultivar × mulch interaction reflected cultivar-specific transparent-film gains of 2.7–3.8 t ha^{-1} and black-film gains of 4.5–5.0 t ha^{-1}. The ordering black > transparent > control held for the three cultivars. The plot-matched yield differences varied among year × block combinations.

Year-averaged marginal comparisons supported black > transparent > control for yield in each cultivar (all Holm-adjusted $p < 0.001$; Table S2). The black-minus-transparent differences were 1.80 t ha^{-1} (1.65–1.95) for Ko'k kalla push, 1.60 t ha^{-1} (1.45–1.75) for Mahalliy Samarqand obi novvoti, and 1.20 t ha^{-1} (1.05–1.35) for Ko'kcha-588. These pointwise confidence intervals refer to the fitted mixed-effects model using the reported experimental data.

The plot-level yield distributions are shown in Figure 2, which displays the spread of observations together with the mean and 95% confidence interval.

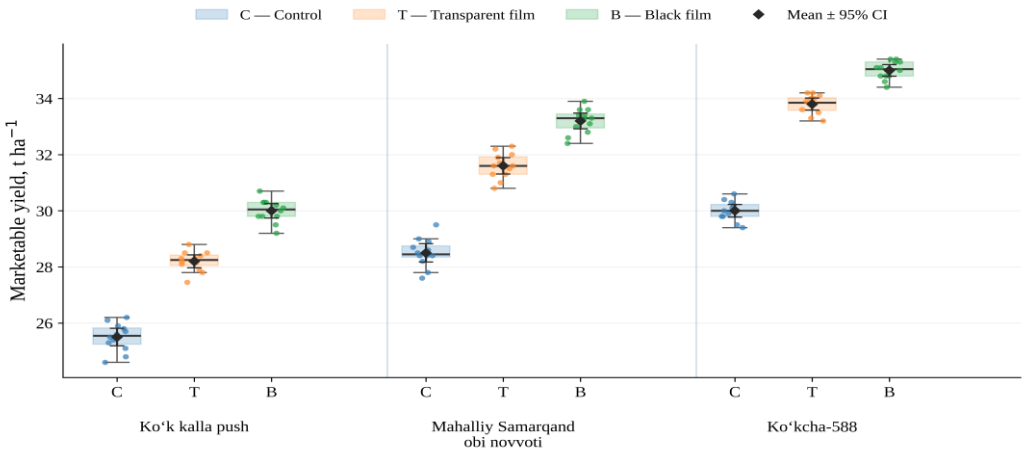


Figure 2. Distribution of marketable melon yield across cultivar × mulch combinations. Boxplots show median and interquartile range; points are the 12 plot-level observations contributing to each three-year treatment mean; diamonds and whiskers show means ± 95% CI.

3.3. Seasonal Irrigation Water and Irrigation Water Productivity

The measured seasonal irrigation across cultivars averaged 4597.2 m^3 ha^{-1} under bare soil, 3947.5 m^3 ha^{-1} with transparent film, and 3748.6 m^3 ha^{-1} with black film. Transparent and black strip mulch, therefore, reduced irrigation input by 649.7 and 848.6 m^3 ha^{-1} (14.1% and 18.5% of mean control irrigation), respectively. The plot-year distributions are shown in Figure 3. Mixed-model marginal comparisons supported lower irrigation for both films within every cultivar (Holm-adjusted $p < 0.001$; Table S2). The year and year × mulch tests were significant in the primary model (Table 1).

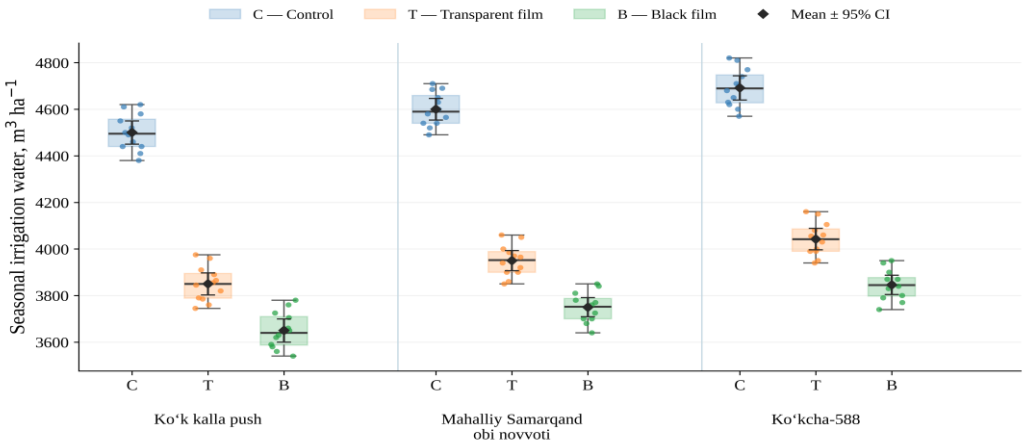


Figure 3. Distribution of measured seasonal irrigation water applied across cultivar × mulch combinations. Each point represents one plot-year observation; diamonds and whiskers show means ± 95% CI.

The IWP was calculated for each plot from its own harvested yield and seasonal irrigation volume. Its grand treatment means were 6.09 kg m^{-3} in the control, 7.90 kg m^{-3} under transparent film, and 8.73 kg m^{-3} under black film, equivalent to increases of 29.7% and 43.4%, respectively. The cultivar-specific mean black-film IWP ranged from 8.22 to 9.10 kg m^{-3}; the highest occurred for Ko'kcha-588 (Figure 4). The plot-level distributions illustrate treatment differences and variation across years and blocks.

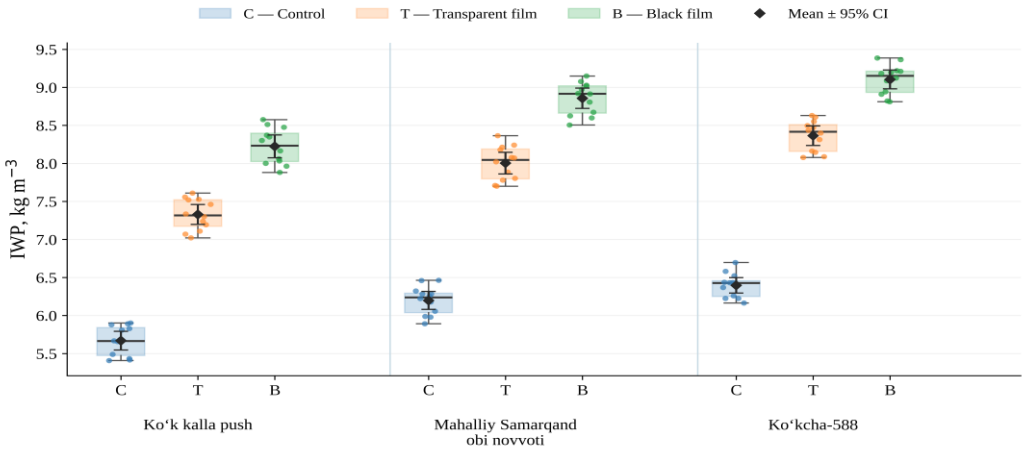


Figure 4. Distribution of irrigation water productivity (IWP) across cultivar × mulch combinations. IWP was calculated independently for every plot from measured irrigation input; diamonds and whiskers show means ± 95% CI.

Table 3 reports the descriptive dispersion among plot-year observations and among annual means. The plot-level yield CV was 6.51–7.59%, while the CV of annual yield means ranged from 0.80% to 1.42%. For IWP, the plot-level CV ranged from 4.93% to 6.09%, and the CV of annual means ranged from 2.44% to 3.26%. These are descriptive statistics for the three observed seasons, not estimates of long-term temporal stability.

Table 3. Complementary plot-level variability and temporal stability derived from Supplementary Data S1.

Mulch	*n*	Yield CV, Plots (%)	Yield CV, Annual Means (%)	Irrigation CV, Plots (%)	Irrigation CV, Annual Means (%)	IWP CV, Plots (%)	IWP CV, Annual Means (%)
Control	36	6.96	1.42	2.38	1.85	5.86	3.26
Transparent film	36	7.58	1.01	2.68	1.82	6.09	2.81
Black film	36	6.51	0.79	2.82	1.74	4.93	2.44

Note: Plot-level CV values were calculated from 36 observations per mulch treatment (3 cultivars × 3 years × 4 blocks). Annual-mean CV values were calculated from the three year-specific treatment means. CV = coefficient of variation.

3.4. Temporal Stability and Paired Technology Effects

The annual treatment means are shown in Figure 5. The black-film treatment maintained the highest mean yield and lowest applied irrigation in each year. Irrigation declined descriptively from 2022 to 2024 in all treatments; the mixed model detected a significant marginal year effect and a year × mulch interaction for irrigation (Table 1). The mean IWP increased across the three years while preserving the following ranking: control < transparent < black. The IWP year × mulch interaction also remained significant ($p = 0.035$). The three seasons did not establish a generalized long-term trend.

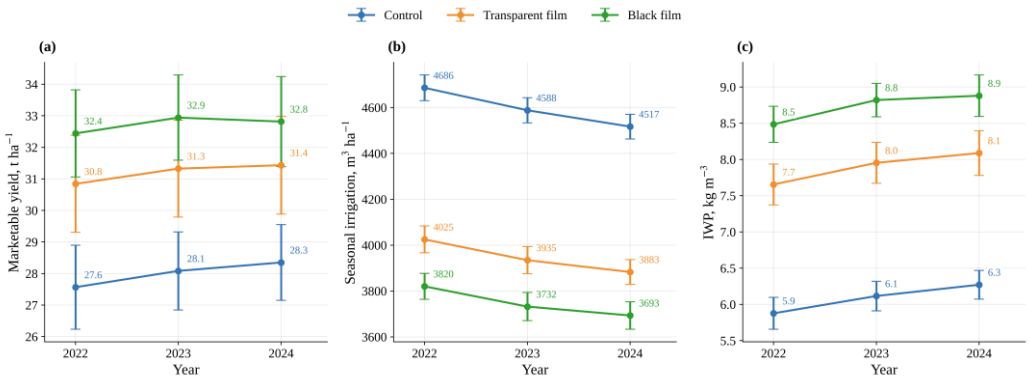


Figure 5. Three-year treatment trajectories for (**a**) marketable yield, (**b**) measured seasonal irrigation water applied, and (**c**) irrigation water productivity. Points are annual treatment means across the three cultivars and four blocks; whiskers show 95% CIs.

Matched plot-level treatment-to-control contrasts were calculated within each cultivar × year × block combination and are summarized in Table 4. The mean yield differences remained at +3.20 and +4.73 t ha^{-1} under transparent and black films; the mean irrigation differences were −649.72 and −848.61 m^3 ha^{-1}; and the mean IWP differences were +1.810 and +2.640 kg m^{-3}, respectively. All six paired descriptive t-tests gave $p < 0.001$. The updated mixed-model contrasts and Holm-adjusted comparisons are reported in Table S2 and constitute the primary inferential results.

Table 4. Matched treatment effects relative to bare soil (n = 36 per film).

Treatment	Response	Mean Difference (95% CI)	SD of Paired Differences	t(35)	Effect, %
Transparent film	Yield, t ha^{-1}	3.200 (3.024 to 3.376)	0.521	36.82	+11.39
	Irrigation, m^3 ha^{-1}	−650 (−658 to −642)	22.99	−169.57	+14.14
	IWP, kg m^{-3}	1.810 (1.758 to 1.863)	0.154	70.39	+29.73
Black film	Yield, t ha^{-1}	4.733 (4.600 to 4.866)	0.393	72.30	+16.95
	Irrigation, m^3 ha^{-1}	−849 (−860 to −837)	33.01	−154.26	+18.46
	IWP, kg m^{-3}	2.640 (2.593 to 2.686)	0.137	115.21	+43.46

Note: Differences are treatment minus matched control; SD and 95% CI refer to absolute differences. Effect (%) is the mean paired percentage change; positive values denote yield/IWP gains or irrigation savings. All paired tests gave $p < 0.001$ (two-sided). Primary inference is reported in Table S2.

For 36 matched comparisons, the transparent-film differences averaged −649.72 m^3 ha^{-1} (SD: 22.99; SE: 3.83; t(35) = −169.57), while the black-film differences averaged −848.61 m^3 ha^{-1} (SD: 33.01; SE: 5.50; t(35) = −154.26). The individual plot values and the frequency distributions of their contrasts are provided in Data S1 and Table S5. These empirical SDs describe dispersion in paired contrasts and are not water-meter calibration errors. A permissible meter error of ±2% is not a lower bound on across-plot SD, and unmeasured systematic calibration errors are not captured by the paired confidence intervals.

Figure 6 summarizes the mean plot-matched relative changes with their 95% confidence intervals. The corresponding transparent-film effects were +11.39% for marketable yield, 14.14% irrigation saving, and +29.73% for IWP; black film produced +16.95%, 18.46% irrigation saving, and +43.46% for IWP. These are the means of the 36 matched percentage differences and, therefore, differ slightly from percentages calculated from overall treatment means. The error bars describe observed paired variation and do not represent meter calibration uncertainty.

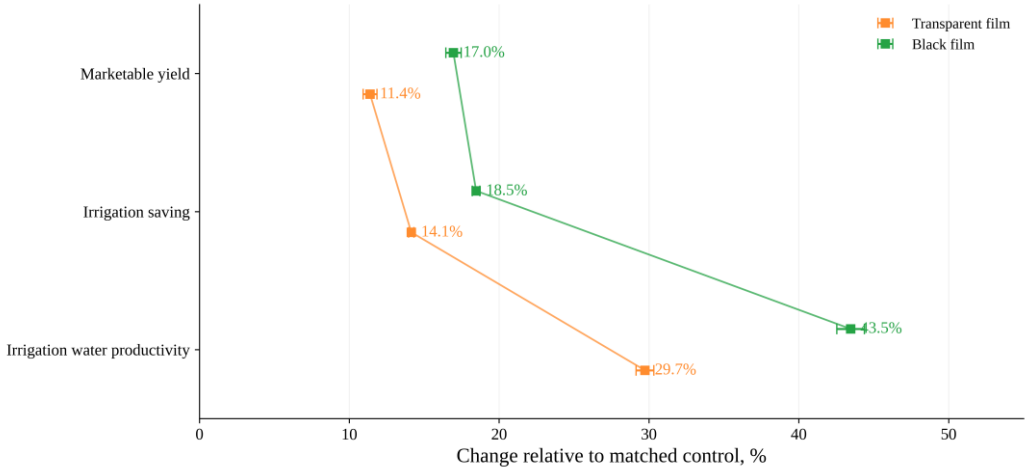


Figure 6. Relative changes in yield, seasonal irrigation, and IWP from matched plot-year observations (n = 36 per film). Symbols show the mean percentage effect relative to the corresponding cultivar × year × block control, with horizontal 95% confidence intervals based on the paired percentages. Lines connect the three displayed indicators only as a visual guide; they do not represent a fitted response surface. Positive irrigation saving denotes reduced applied water.

3.5. Integrated Resource Output Performance

Figure 7 presents two analytical contour maps. Panel (a) displays the identity IWP = 1000Y/*I* over the observed yield and irrigation ranges, with the nine cultivar × treatment means superimposed. It is an algebraic visualization, not an independently fitted response surface or evidence of a biological optimum. Panel (b) shows the price-dependent incremental margin for black strip mulch before additional labor and end-of-life costs. Its zero contour is the film-cost break-even boundary.

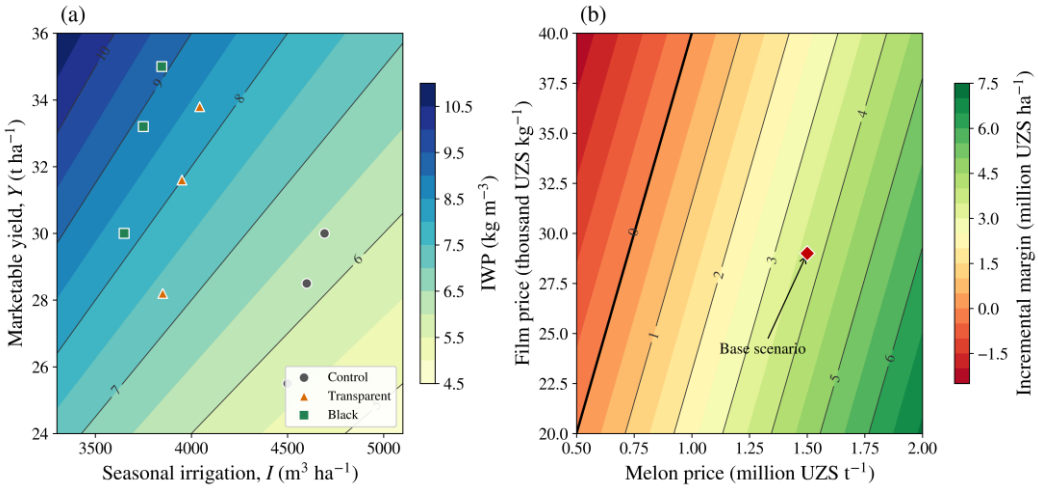


Figure 7. Analytical resource output and price sensitivity maps: (**a**) IWP calculated from marketable yield and applied irrigation, with symbols marking the nine cultivar × mulch mean coordinates; (**b**) incremental margin for black strip mulch calculated from its mean yield advantage and film input. Contours show calculated values, not fitted biological responses. The heavy zero contour in panel (**b**) is the break-even boundary; the red diamond identifies the base price scenario. Additional labor, water charges, energy, and end-of-life costs are excluded.

For interpretation of the IWP surface, its local sensitivities to yield and irrigation input follow directly from Equation (17):

$$\mathrm{IWP}(Y,I)=\frac{10^3 Y}{I},\qquad \frac{\partial \mathrm{IWP}}{\partial Y}=\frac{10^3}{I},\qquad \frac{\partial \mathrm{IWP}}{\partial I}=-\frac{10^3 Y}{I^2} \tag{17}$$

Thus, at a fixed irrigation input, the IWP increases linearly with yield, whereas at a fixed yield, the response to additional irrigation is negative and proportional to I^{-2}. These derivatives describe the geometry of Figure 7a and were not fitted as an additional biological response model.

3.6. Polymer Use, Mulch Use Efficiency, and Plastic Load

The 42.9% strip configuration required 118.3 kg polyethylene ha^{-1}, compared with a calculated 276.0 kg ha^{-1} material requirement for 100% coverage at the same thickness. The resulting 157.7 kg ha^{-1} reduction corresponds to 57.1% less polymer entering the production system. At a scale of 1000 ha, the same configuration would avoid approximately 157.7 t of film per season before any downstream collection or recycling is considered.

Film-use efficiency favored black film (Table 5). Depending on cultivar, the black-film MUE ranged from 38.04 to 42.27 kg additional fruit kg^{-1} film, compared with 22.82–32.12 kg kg^{-1} for transparent film. The plastic intensity was 3.38–3.94 kg film t^{-1} fruit for black film and 3.50–4.20 kg t^{-1} for transparent film. Across cultivars, black film saved approximately 7.18 m^3 irrigation water per kilogram of film applied, compared with

approximately 5.49 m^3 kg^{-1} for transparent film; exact cultivar-specific ratios appear in Table 5. The combined co-benefit indicator ranged from approximately 529 to 591 kg additional marketable fruit per 100 m^3 irrigation saved under black film. With a virgin-LDPE screening factor of 1.87 kg CO_2-eq kg^{-1}, the 157.7 kg ha^{-1} calculated polymer reduction relative to full-surface coverage corresponds to approximately 295 kg CO_2-eq ha^{-1} of potentially avoided virgin-resin production emissions. This is not a full life-cycle result or a measured reduction in soil plastic residues.

Table 5. Cultivar-specific film-use and combined yield–water efficiency indicators derived from the three-year treatment means.

Cultivar	Mulch	MUE, kg Fruit kg^{-1} Film	Plastic Intensity, kg Film t^{-1} Fruit	Water Saved per kg Film, m^3 kg^{-1}	Additional Yield Per 100 m^3 Saved, kg
Ko'k kalla push	Transparent film	22.82	4.20	5.49	415.4
Ko'k kalla push	Black film	38.04	3.94	7.19	529.4
Mahalliy Samarqand obi novvoti	Transparent film	26.20	3.74	5.49	476.9
Mahalliy Samarqand obi novvoti	Black film	39.73	3.56	7.19	552.9
Ko'kcha-588	Transparent film	32.12	3.50	5.49	585.4
Ko'kcha-588	Black film	42.27	3.38	7.15	591.1

Note: MUE = additional marketable fruit relative to the cultivar control per kilogram of strip film. Plastic intensity = strip-film mass per ton of marketable yield. Water saved per kilogram of film and additional yield per 100 m^3 of irrigation saved are derived co-benefit indicators. Strip-film input was 118.3 kg ha^{-1} for both film colors.

3.7. Economic Performance and Sensitivity

Localized placement reduced the film-material cost by 3.63–5.52 million UZS ha^{-1} relative to the calculated full-surface material requirement. At the assumed melon price, the strip-film cost corresponded to a break-even yield increase of approximately 1.8–2.8 t ha^{-1}. The observed yield gains under black film (4.5–5.0 t ha^{-1}) exceeded this range for all cultivars. Transparent film produced a smaller margin, particularly for Ko'k kalla push. To separate biological observations from market assumptions, the economic sensitivity analysis was performed only on the accounting layer; no additional biological response was inferred outside the experimental treatments.

The economic sensitivity component (Figure 7b) was constructed directly from Equation (10), using the observed across-cultivar mean black-film yield advantage (4.73 t ha^{-1}) and the strip-film material requirement. The map spans a scenario range of 0.5–2.0 million UZS t^{-1} for melon price and 20–40 thousand UZS kg^{-1} for film price. At the base scenario used in the economic calculations (1.5 million UZS t^{-1} melon and 29,000 UZS kg^{-1} film), black strip mulch generated approximately 3.67 million UZS ha^{-1} of incremental margin before uncosted operations relative to the control. Across the originally evaluated film-price range of 23,000–35,000 UZS kg^{-1}, the break-even melon price was approximately 0.57–0.87 million UZS t^{-1}. This map is an economic scenario analysis derived from the measured yield effect rather than a biological response map regression.

In the base scenario, the mean incremental margins were 1.37 million UZS ha^{-1} for transparent film and 3.67 million UZS ha^{-1} for black film. Additional uncosted operations totaling 1.0, 2.0, or 3.0 million UZS ha^{-1} would reduce these margins to 0.37, −0.63, and −1.63 million UZS ha^{-1} for transparent film, and 2.67, 1.67, and 0.67 million UZS ha^{-1} for black film. These allowances are illustrative scenarios, not measured labor costs. At 35,000 UZS kg^{-1} film and 1.5 million UZS t^{-1} melon, transparent film for Ko'k kalla push gives an incremental margin of approximately −0.09 million UZS ha^{-1} even before these additional costs.

The cultivar-specific partial-budget net-income and profitability estimates are shown in Figure 8. The highest estimated net income was obtained from Ko'kcha-588 with black film, at 30.36–31.78 million UZS ha^{-1} across the evaluated film-price range. Profitability percentages did not always increase with mulching because film enlarged the cost base, even when absolute net income increased. The estimates remain conditional on the included cost boundary and should not be interpreted as realized commercial profit.

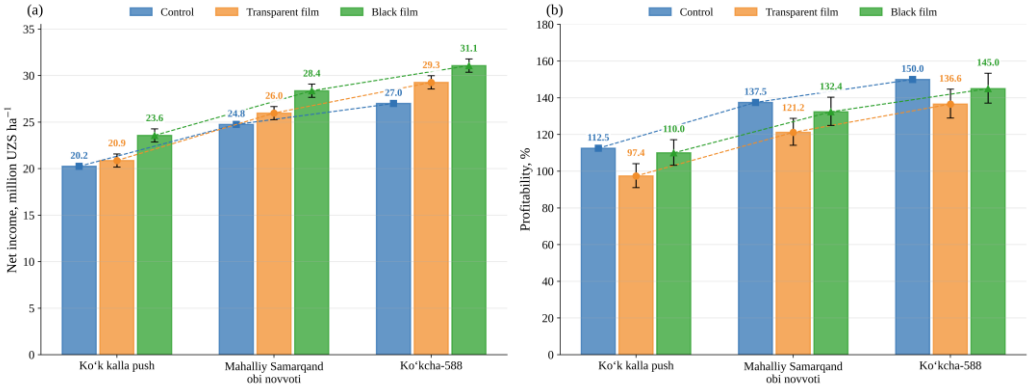


Figure 8. Partial-budget net income and profitability of melon cultivation by cultivar and mulching treatment: (**a**) net income, million UZS ha^{-1}; (**b**) profitability, %. Bars show values at the mid-range film price (29,000 UZS kg^{-1}); whiskers (film treatments only) show the range corresponding to 23,000–35,000 UZS kg^{-1}. Colored markers and dashed lines connect treatment means across cultivars for visual comparison only and do not represent regression or interpolation; numerical labels indicate treatment means. Values exclude separately uncosted installation, removal, irrigation labor, and end-of-life operations; whiskers represent price scenarios, not statistical confidence intervals.

3.8. Soil Temperature and Weed Biomass

The measured soil temperature profiles showed consistently stronger warming under transparent film than under black film. Across the three seasons, the mean temperatures at 5, 10 and 20 cm were 34.0, 31.4 and 28.2 °C under transparent film, versus 27.3, 25.0 and 22.7 °C in bare soil (Table 6). Thus, the respective differences were approximately +6.7, +6.4 and +5.5 °C. Black film produced corresponding means of 29.7, 27.4 and 24.5 °C, exceeding the control by approximately +2.4, +2.4 and +1.8 °C. Both film-associated differences decreased with depth. Annual values and their SDs are provided in Table S7; the displayed three-year SDs describe variation among annual means and do not constitute independent treatment-effect SEs.

Table 6. Three-year mean soil temperature at 5, 10 and 20 cm under the tested soil-cover treatments (2022–2024).

Treatment	5 cm (°C)	10 cm (°C)	20 cm (°C)
Bare soil	27.3 ± 0.3	25.0 ± 0.2	22.7 ± 0.2
Transparent film	34.0 ± 0.2	31.4 ± 0.3	28.2 ± 0.2
Black film	29.7 ± 0.2	27.4 ± 0.2	24.5 ± 0.2

Note: Values are means ± sample SD of the three annual treatment means (n = 3 years). Each annual mean was computed from 24 cultivar × block × date daily means; each daily mean was based on eight within-day thermometer readings. The data are pooled descriptively across cultivars.

In the 25 June 2024 sampling of the uncovered 2.00 m wide inter-row strips, the mean aboveground dry weed biomass was 41.9 ± 2.7 g m^{-2} in bare soil, 23.2 ± 2.5 g m^{-2} with transparent film, and 8.2 ± 1.1 g m^{-2} with black film (mean ± sample SD; n = 4 blocks). Compared with the control, the uncovered-strip biomass was lower by 44.7% and 80.4%,

respectively. Block-level observations are reported in Table S8. These values do not quantify weeds beneath the film or biomass over the full hectare; the single sampling date does not establish a season-long weed response.

4. Discussion

The results support treating strip mulching as a material application technology rather than simply as a crop-cover treatment. The tested 42.9% coverage geometry required 57.1% less polymer than the calculated full-coverage benchmark. Separately, both film treatments increased yield and reduced measured irrigation relative to bare soil. This combination is important because the agronomic function of the film was concentrated in the row zone within the tested paired-row geometry. In engineering terms, the technology increased output per unit of polymer while also lowering the seasonal water input needed to maintain the same pre-irrigation soil moisture threshold.

The measured outcome was reduced applied irrigation under a common moisture threshold rule; soil evaporation was not measured. Reduced evaporation is one plausible explanation, supported by the greenhouse melon experiment of Liu et al. [11], which directly examined interplant evaporation under mulched and un-mulched irrigation. Wang et al. [12] and Li et al. [13] independently showed that soil moisture thresholds influence melon yield and water use, although their environments and irrigation systems differed. These studies support the scheduling rationale and possible mechanism, not the direct transfer of their effect sizes to the present field. The measured savings of approximately 650–849 m^3 ha^{-1} correspond to 65–85 mm of applied water per season. This is a practically relevant reduction in field delivery under the tested conditions; it is not a demonstrated reduction in basin-scale consumptive use. Earlier greenhouse muskmelon studies that varied covering fraction, drip-line arrangements and irrigation thresholds [32,33] lend context to the moisture management rationale, but their crop environments are not directly comparable with the present arid-field observations.

Evidence from long-term semi-arid maize systems also supports treating soil-surface engineering and water management as interacting components rather than independent inputs. Conservation tillage has been shown to modify soil water storage, crop yield, and water-use efficiency, with the magnitude of the response depending strongly on seasonal rainfall distribution [49]. Field work on local loosening in soybean [16] similarly reinforces that altered soil management may affect crop response without establishing the particular mechanism operating beneath melon mulch.

Additional crop management evidence comes from a winter-wheat cultivation study [50] and a fertilization trial with white cabbage [36]. As with the previously cited soybean results [16], these findings are used for broader agronomic context rather than as direct evidence of the mechanisms behind the melon responses observed here.

Black polyethylene transmits less photosynthetically active radiation than transparent film, while transparent film generally provides stronger radiative soil warming [1,2]. The present field measurements support the thermal contrast: across 2022–2024, transparent film produced higher mean soil temperatures than black film at all three observed depths (Table 6). On 25 June 2024, black-film plots also had the lowest weed dry biomass within the sampled uncovered 2.00 m inter-row strips (Table S8). This local weed result should not be interpreted as a direct measurement beneath the film or as evidence for the entire plot. The joint observations are consistent with different thermal and weed-development environments under the two treatments. However, these measurements do not partition the independent effects of temperature, light exclusion, weed competition and soil-water dynamics on melon yield or irrigation demand. Black film retained the highest marketable yield and the lowest applied irrigation across the tested cultivars; a causal decomposition of those advantages requires additional targeted experiments.

The cultivar × mulch interaction for yield indicates that the response was not purely additive across cultivars. Ko'kcha-588 had the highest absolute yield and the largest transparent-film increment, while black-film gains remained positive in all three cultivars. The marginal tests also detected year × mulch interactions for yield, irrigation, and IWP and a cultivar × mulch interaction for IWP, while cultivar × mulch was not significant for irrigation. Thus, the direction of the mulch effect was consistent, but its magnitude depended on genotype and season. These findings should be interpreted in light of the residual diagnostic limitations stated above.

Lower polymer input is the second major technology outcome. Reviews of agricultural plastics emphasize that incomplete recovery, contamination with soil, fragmentation, and end-of-life handling remain persistent problems [5–8,28–31]. Recycling can lower the climate burden of LDPE film, but contaminated agricultural film can be costly to collect and process [28,29,48]. Source reduction, therefore, has a different role from recycling: it reduces the mass that must enter the end-of-life system at all. At 157.7 kg ha^{-1} less film than the full-surface material benchmark, the strip configuration reduces the nominal material mass requiring procurement and eventual management. The screening GHG calculation relates only to avoided virgin-LDPE resin production. It excludes film extrusion and other life-cycle stages and must not be interpreted as a complete life-cycle assessment. No recovery percentage or reduction in residual microplastics was measured.

Biodegradable films remain an important complementary pathway. Melon trials have shown that biodegradable materials can sustain competitive yield and quality [24–26], while broader crop studies show that performance depends on material properties and field environment [27]. Life-cycle evidence also indicates that no single film option is environmentally superior under every production and end-of-life scenario [28]. A practical next step is, therefore, not simply to replace polyethylene with another material, but to combine low material intensity with films designed for easier recovery, recycling, or soil biodegradation. The strip geometry tested here provides a geometric basis for such comparisons, but alternative films would require testing at their own thickness, density, durability, and recovery conditions.

The economic assessment identifies the yield increment needed to cover film purchase under stated prices. Black film exceeded that threshold for each cultivar over the evaluated film-price range. However, omitted labor and end-of-life costs can reduce the calculated margin, while monetized water or energy savings could increase it. The additional-cost sensitivity quantifies this balance without assuming local wage rates or tariffs. Mechanized placement and retrieval warrant separate operational testing [37–39]. The present calculation supports a conditional partial-budget comparison, not a claim of universal commercial profitability.

Future mechanization should be evaluated separately from the manual strip installation tested here. Experimental work on flexible soil-working elements [41], flat-blade geometry [42], and rotary cultivator points [43] provides examples of engineering parameters that may affect soil preparation. Related strip-tillage field research in semi-arid vineyards [14] and an engineering review of seedbed preparation in water-limited systems [15] indicate directions for future machinery trials, rather than operational savings measured in the present experiment.

Cultivar and mulch are categorical experimental factors. The analytical IWP and price maps, therefore, describe arithmetic relationships and economic scenarios; they are not response-surface regressions and do not identify an experimentally validated optimum. Their role is to make the resource accounting explicit alongside the mixed-model treatment comparisons.

Under the tested conditions, black strip mulch combined higher marketable yield with lower applied irrigation than bare soil and used less polymer than the theoretical full-coverage material benchmark. These are distinct comparisons. The results support further evaluation of the geometry as a resource-efficient option while leaving full-surface agronomic performance, residual plastics, and complete environmental and commercial outcomes unresolved.

5. Study Limitations

The experiment covered one site, three cultivars, and three seasons, retaining the same four physical blocks with annual treatment re-randomization. Within-block comparisons are supported, but carry-over and temporal dependence cannot be excluded. The primary mixed models detected year-related changes, and Table S4 compares their fixed-effect tests with an alternative persistent-block covariance specification. The IWP alternative fit showed a boundary warning; the irrigation and IWP residuals departed from normality. Consequently, nominal Wald *p*-values should be interpreted cautiously, and broader temporal or geographic inference requires independent validation.

Second, the measured water variable was seasonal irrigation water applied, not crop evapotranspiration. Individual flow meters provide direct evidence for irrigation saving, but the experiment did not partition soil evaporation and crop transpiration or measure drainage. Accordingly, IWP is reported as irrigation water productivity and should not be interpreted as evapotranspiration water productivity.

Third, soil temperature was monitored on two dates per year during emergence to early flowering, whereas aboveground weed biomass was sampled only once (25 June 2024) in the uncovered 2.00 m inter-row strips. Temperature was not continuously logged throughout the season, and weed biomass was not measured under the films or over the total plot surface. These complementary observations support interpretation of film-associated thermal differences and localized weed development but do not directly quantify whole-season weed suppression, evaporation, transpiration or the independent contributions of the mechanisms to yield.

Further limitations concern the use of regional meteorological station records rather than an on-plot weather station, unavailable irrigation water chemistry, and the absence of additional soil chemical characterization. The monthly climate series covers complete April–August calendar months rather than exact sowing-to-harvest intervals. Soluble solids and firmness were not measured. Data S1 contains seasonal plot-year observations; individual gram-level harvest records, irrigation-event meter logs, and individual temperature time-series readings are not included in the supplied supplementary package. Meter calibration uncertainty was not propagated, and an illustrative ±2% scenario cannot establish the field-meter accuracy outside its specified operating range.

Fourth, full-surface mulching was not included as an experimental treatment. The 276.0 kg ha^{-1} value is a calculated material benchmark for 100% coverage at the same film thickness, and material-input and film-purchase comparisons against it concern polymer requirement, not a directly measured full-surface yield response. The GHG estimate is likewise a screening calculation based on a literature factor for virgin LDPE resin production. A future study should include an experimental full-surface treatment and a complete life-cycle assessment incorporating resin production, film extrusion, transport, field installation, removal, cleaning, recycling or disposal, irrigation energy, and mechanization. Economic prices and the common production cost allowance are scenario inputs; omitted operational costs and unvalued irrigation savings prevent interpretation as a complete farm-profit estimate.

6. Conclusions

The three-year RCBD experiment showed that localized strip application of 30 µm of polyethylene increased marketable yield and reduced seasonal irrigation applied relative to bare soil under the tested conditions. Covering 42.9% of the field required 118.3 kg film ha^{-1}, 57.1% below the calculated requirement for full-surface coverage. Transparent and black strip mulch increased the mean marketable yield by 11.4% and 16.9% while reducing seasonal applied irrigation by 14.1% and 18.5%, respectively.

Black film provided the strongest combined response. Across cultivars, the mean plot-level IWP increased from 6.09 kg m^{-3} in the bare-soil control to 8.73 kg m^{-3} under black film, and the black-film MUE ranged from 38.04 to 42.27 kg additional fruit kg^{-1} film. Ko'kcha-588 under black strip mulch averaged 35.0 t ha^{-1}, 3845.8 m^3 ha^{-1} of seasonal irrigation, and 9.10 kg m^{-3} of IWP. The strip geometry also avoided a calculated 157.7 kg ha^{-1} of polyethylene relative to full-surface coverage and lowered the nominal film purchase cost by 3.63–5.52 million UZS ha^{-1}.

Complementary soil measurements found stronger upper-profile warming under transparent film (6.7, 6.4 and 5.5 °C above bare soil at 5, 10 and 20 cm, respectively) than under black film (2.4, 2.4 and 1.8 °C). In the uncovered inter-row strips sampled on 25 June 2024, black film had the lowest weed biomass (8.2 ± 1.1 g m^{-2}, compared with 41.9 ± 2.7 g m^{-2} in bare soil). These are depth- and sampling-domain-specific observations, not a quantitative attribution of the crop response to thermal or weed mechanisms.

These results support the potential of strip mulching as a resource-efficient technology under the tested conditions. They do not establish agronomic equivalence to full-surface mulch or overall life-cycle superiority. Further work should evaluate full-surface and alternative-film treatments, operational costs, film recovery, and performance across independent sites and seasons.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/technologies14110750/s1. Data S1 contains 108 seasonal plot-year yield, irrigation and IWP observations from the 2022–2024 experiments. Figure S1 provides residual diagnostics. Tables S1–S5 present estimated marginal means, adjusted contrasts, economic assumptions, model sensitivity and irrigation contrast frequencies. Tables S6–S9 document the Samarkand Station monthly meteorology, annual soil temperature summaries, block-level weed biomass and sowing/harvest dates, respectively.

Author Contributions: Conceptualization, X.A. and S.M.; methodology, X.A., S.M. and I.R.; software, I.R. and J.E.; validation, M.K. and S.S.; formal analysis, X.R. and I.R.; investigation, S.S., S.A., A.K., J.E. and I.N.; resources, S.A. and I.N.; data curation, S.S. and J.E.; writing—original draft preparation, X.A.; writing—review and editing, S.M., M.K. and S.T.; visualization, X.R.; supervision, X.A.; project administration, X.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Seasonal plot-year yield, irrigation and derived IWP data for 108 observations are supplied as Supplementary Data S1. The supplementary package also contains monthly JMA meteorological values, author-reported aggregated soil temperature measurements and four-block weed biomass observations. The original 192 temperature readings per treatment × depth × year and their 24 underlying daily means have not been supplied in the supplement; reported temperature SDs are, therefore, not independently recalculable from the supplementary summaries alone. Individual gram-level harvest records and irrigation-event meter logs are also not included. Additional data are available from the corresponding author upon reasonable request.

https://doi.org/10.3390/technologies14110750

Acknowledgments: The authors thank the "Ishonch" farm (Nurabad district, Samarkand region) for providing the experimental field site. Gemini 2.5 Flash (developed by Google) was used during manuscript revision to assist with language editing.

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

References

1. Kasirajan, S.; Ngouajio, M. Polyethylene and biodegradable mulches for agricultural applications: A review. *Agron. Sustain. Dev.* **2012**, *32*, 501–529. https://doi.org/10.1007/s13593-011-0068-3. Erratum in *Agron. Sustain. Dev.* **2013**, *33*, 443.
2. Kader, M.A.; Senge, M.; Mojid, M.A.; Ito, K. Recent advances in mulching materials and methods for modifying soil environment. *Soil Tillage Res.* **2017**, *168*, 155–166. https://doi.org/10.1016/j.still.2017.01.001.
3. Gao, H.; Yan, C.; Liu, Q.; Ding, W.; Chen, B.; Li, Z. Effects of plastic mulching and plastic residue on agricultural production: A meta-analysis. *Sci. Total Environ.* **2019**, *651*, 484–492. https://doi.org/10.1016/j.scitotenv.2018.09.105.
4. Steinmetz, Z.; Wollmann, C.; Schaefer, M.; Buchmann, C.; David, J.; Tröger, J.; Muñoz, K.; Frör, O.; Schaumann, G.E. Plastic mulching in agriculture. Trading short-term agronomic benefits for long-term soil degradation? *Sci. Total Environ.* **2016**, *550*, 690–705. https://doi.org/10.1016/j.scitotenv.2016.01.153.
5. Khalid, N.; Aqeel, M.; Noman, A.; Rizvi, Z.F. Impact of plastic mulching as a major source of microplastics in agroecosystems. *J. Hazard. Mater.* **2023**, *445*, 130455. https://doi.org/10.1016/j.jhazmat.2022.130455.
6. Qiang, L.; Hu, H.; Li, G.; Xu, J.; Cheng, J.; Wang, J.; Zhang, R. Plastic mulching, and occurrence, incorporation, degradation, and impacts of polyethylene microplastics in agroecosystems. *Ecotoxicol. Environ. Saf.* **2023**, *263*, 115274. https://doi.org/10.1016/j.ecoenv.2023.115274.
7. Salama, K.; Geyer, M. Plastic mulch films in agriculture: Their use, environmental problems, recycling and alternatives. *Environments* **2023**, *10*, 179. https://doi.org/10.3390/environments10100179.
8. El-Beltagi, H.S.; Basit, A.; Mohamed, H.I.; Ali, I.; Ullah, S.; Kamel, E.A.R.; Shalaby, T.A.; Ramadan, K.M.A.; Alkhateeb, A.A.; Ghazzawy, H.S. Mulching as a sustainable water and soil saving practice in agriculture: A review. *Agronomy* **2022**, *12*, 1881. https://doi.org/10.3390/agronomy12081881.
9. Ramos, T.B.; Darouich, H.; Pereira, L.S. Mulching effects on soil evaporation, crop evapotranspiration and crop coefficients: A review aimed at improved irrigation management. *Irrig. Sci.* **2024**, *42*, 525–539. https://doi.org/10.1007/s00271-024-00924-8.
10. Wang, C.; Li, S.; Huang, S.; Feng, X. A review of the application and impact of drip irrigation under plastic mulch in agricultural ecosystems. *Agronomy* **2024**, *14*, 1752. https://doi.org/10.3390/agronomy14081752.
11. Liu, S.; Li, J.; Jia, S.; Dai, Z.; Du, F.; Zhao, N.; Fan, F.; Liu, Z.; Zhao, S. Effects of irrigation approaches and mulching on greenhouse melon production and water use in Northern China. *Water* **2024**, *16*, 2013. https://doi.org/10.3390/w16142013.
12. Wang, J.; Huang, G.; Li, J.; Zheng, J.; Huang, Q.; Liu, H. Effect of soil moisture-based furrow irrigation scheduling on melon (*Cucumis melo* L.) yield and quality in an arid region of Northwest China. *Agric. Water Manag.* **2017**, *179*, 167–176. https://doi.org/10.1016/j.agwat.2016.04.023.
13. Li, Y.-J.; Yuan, B.-Z.; Bie, Z.-L.; Kang, Y. Effect of drip irrigation criteria on yield and quality of muskmelon grown in greenhouse conditions. *Agric. Water Manag.* **2012**, *109*, 30–35. https://doi.org/10.1016/j.agwat.2012.02.003.
14. Syromiatnykov, Y.; Mamatov, F.; Sholoiko, A.; Galych, I.; Irgashev, D.; Ravshanov, K.; Ravshanova, N.; Ergashov, G.; Rajabov, Y.; Aliev, B.; et al. Geometry-optimized strip tillage for improving soil physical quality and hydraulic function in semi-arid vineyards. *Agriculture* **2026**, *16*, 751. https://doi.org/10.3390/agriculture16070751.
15. Syromiatnykov, Y.; Mamatov, F.; Toshtemirov, S.; Kurbanov, S.; Kodirov, U.; Choriyeva, D.; Shodmonov, G.; Begimkulova, M.; Jalilov, S.; Safarov, A.; et al. Design and optimization of soil-engaging components for intelligent seedbed preparation in water-limited cropping systems: A critical review. *AgriEngineering* **2026**, *8*, 376. https://doi.org/10.3390/agriengineering8090376.
16. Pashchenko, V.F.; Syromyatnikov, Y.N.; Khramov, N.S.; Voinash, S.A. The influence of local loosening of the soil on soybean productivity. *Tract. Agric. Mach.* **2019**, *86*, 79–86. https://doi.org/10.31992/0321-4443-2019-5-79-86.
17. Adamczewska-Sowińska, K. The use of soil surface mulching on melon (*Cucumis melo* L.) production under temperate climate conditions. *Agriculture* **2024**, *14*, 1398. https://doi.org/10.3390/agriculture14081398.
18. Buczkowska, H.; Nurzyńska-Wierdak, R. Fruiting of melon (*Cucumis melo* L.) grown organically on mulched soil. *Acta Sci. Pol. Hortorum Cultus* **2020**, *19*, 121–131. https://doi.org/10.24326/asphc.2020.4.11.

19. Kosterna, E.; Zaniewicz-Bajkowska, A.; Franczuk, J.; Rosa, R.; Chromińska, K.; Borysiak-Marciniak, I.; Panasz, M. Effect of synthetic mulches on melon (*Cucumis melo* L.) yielding. *Folia Hortic.* **2011**, *23*, 151–156. https://doi.org/10.2478/v10245-011-0023-4.
20. Iapichino, G.; Mustazza, G.; Sabatino, L.; D'Anna, F. Polyethylene and biodegradable starch-based mulching films positively affect winter melon production in Sicily. *Acta Hortic.* **2014**, *1015*, 225–231. https://doi.org/10.17660/ActaHortic.2014.1015.25.
21. Birbal, B.; Soni, M.L.; Rathore, V.S.; Nathawat, N.S.; Renjith, P.S. Interactive effect of FYM and mulching on productivity and water use efficiency of squash melon (Citrullus vulgaris var. fistulosus) grown with supplemental irrigation in hot arid region of Rajasthan. *Indian J. Agric. Sci.* **2019**, *89*, 307–313. https://doi.org/10.56093/ijas.v89i2.87090.
22. Pawar, P.S.; Kadale, A.S.; Gadade, G.D. Effect of different mulches on soil moisture conservation and yield of drip irrigated watermelon. *Indian J. Soil Conserv.* **2019**, *47*, 134–142. Available online: https://ijsc.iaswc.com/index.php/ijsc/article/view/268 (accessed on 1 November 2026).
23. Kaur, J.; Singh, K.; Singh, K.G.; Sharma, S.P.; Talwar, D. Effect of drip irrigation, fertigation and mulch on quality of muskmelon. *Agric. Res. J.* **2021**, *58*, 1060–1064. https://doi.org/10.5958/2395-146X.2021.00149.6.
24. Cozzolino, E.; Di Mola, I.; Ottaiano, L.; Bilotto, M.; Petriccione, M.; Ferrara, E.; Mori, M.; Morra, L. Assessing yield and quality of melon (*Cucumis melo* L.) improved by biodegradable mulching film. *Plants* **2023**, *12*, 219. https://doi.org/10.3390/plants12010219.
25. Sellami, M.H.; Di Mola, I.; Ottaiano, L.; Cozzolino, E.; del Piano, L.; Mori, M. Evaluation of biodegradable mulch films on melon production and quality under Mediterranean field conditions. *Agronomy* **2024**, *14*, 2075. https://doi.org/10.3390/agronomy14092075.
26. Filippi, F.; Magnani, G.; Guerrini, S.; Ranghino, F. Agronomic evaluation of green biodegradable mulch on melon crop. *Ital. J. Agron.* **2011**, *6*, e18. https://doi.org/10.4081/ija.2011.e18.
27. Wang, Z.; Li, M.; Flury, M.; Schaeffer, S.M.; Chang, Y.; Tao, Z.; Jia, Z.; Li, S.; Ding, D.; Wang, J. Agronomic performance of polyethylene and biodegradable plastic film mulches in a maize cropping system in a humid continental climate. *Sci. Total Environ.* **2021**, *786*, 147460. https://doi.org/10.1016/j.scitotenv.2021.147460.
28. Tan, Q.; Yang, L.; Wei, F.; Chen, Y.; Li, J. Comparative life cycle assessment of polyethylene agricultural mulching film and alternative options including different end-of-life routes. *Renew. Sustain. Energy Rev.* **2023**, *178*, 113239. https://doi.org/10.1016/j.rser.2023.113239.
29. Madrid, B.; Wortman, S.; Hayes, D.G.; DeBruyn, J.M.; Miles, C.; Flury, M.; Marsh, T.L.; Galinato, S.P.; Englund, K.; Agehara, S.; et al. End-of-life management options for agricultural mulch films in the United States—A review. *Front. Sustain. Food Syst.* **2022**, *6*, 921496. https://doi.org/10.3389/fsufs.2022.921496.
30. Seo, Y.; Zhou, Z.; Lai, Y.; Chen, G.; Pembleton, K.; Wang, S.; He, J.-Z.; Song, P. Micro- and nanoplastics in agricultural soils: Assessing impacts and navigating mitigation. *Sci. Total Environ.* **2024**, *931*, 172951. https://doi.org/10.1016/j.scitotenv.2024.172951.
31. Shafea, L.; Yap, J.; Beriot, N.; Felde, V.J.M.N.L.; Okoffo, E.D.; Enyoh, C.E.; Peth, S. Microplastics in agroecosystems: A review of effects on soil biota and key soil functions. *J. Plant Nutr. Soil Sci.* **2023**, *186*, 5–22. https://doi.org/10.1002/jpln.202200136.
32. Wang, J.; Niu, W.; Li, Y. Effects of drip irrigation with plastic on photosynthetic characteristics and biomass distribution of muskmelon. *Agriculture* **2020**, *10*, 84. https://doi.org/10.3390/agriculture10030084.
33. Wang, J.; Niu, W.; Xu, J.; Li, Y. Effects of drip irrigation under plastic film on muskmelon soil environment and yield in greenhouse. *Trans. Chin. Soc. Agric. Eng.* **2016**, *32*, 232–241. https://doi.org/10.11975/j.issn.1002-6819.2016.06.032.
34. Karimov, A.; Khalikov, B.; Isaev, S.; Sindarov, O.; Khayitov, K.; Avliyakulov, M.; Isashov, A.; Bulanbayeva, P.; Djumanazarova, A.; Muhammadov, Y.; et al. Efficiency of drip irrigation in amaranth production using the HYDRUS-1D model. *Front. Sustain. Food Syst.* **2025**, *9*, 1612679. https://doi.org/10.3389/fsufs.2025.1612679.
35. Gulyarenko, A.; Malikov, V.; Orekhovskaya, A. Dynamics of agrophysical parameters and corn yield under minimum tillage in Samarkand region. *Acta Technol. Agric.* **2025**, *28*, 80–87. https://doi.org/10.2478/ata-2025-0011.
36. Kuts, O.; Kokoiko, V.; Mykhailyn, V.; Syromyatnikov, Y.; Zhernova, O. Fertilisation system influence on the main agrochemical indicators of soil and productivity of white cabbage. *Sci. Horiz.* **2023**, *26*, 69–79. https://doi.org/10.48077/scihor11.2023.69.
37. Karshiev, F.; Chuyanov, D.; Eshdavlatov, E.; Ismailov, I.; Temirov, I.; Eshdavlatov, A.; Gulomov, L.; Abduganiyeva, S.; Jalilov, S. Optimization of leveler–compactor parameters in combined strip tillage for soil preparation under plastic film for melon crops. *Agronomy* **2026**, *16*, 809. https://doi.org/10.3390/agronomy16080809.

38. Mamatov, F.; Fayzullaev, K.; Ravshanova, N.; Gulomov, L.; Abduganiyeva, S. Experimental results of a combined machine for soil preparation and plastic film laying in melon crop production. *E3S Web Conf.* **2026**, *703*, 03015. https://doi.org/10.1051/e3sconf/202670303015.
39. Ramadan, Y.Y.; Moustafa, M.M.; Cottb, M. Development of a plastic mulching machine. *Misr J. Agric. Eng.* **2014**, *31*, 19–42. https://doi.org/10.21608/mjae.2014.99688.
40. Harshavardhan, K.; Shrivastava, A.K.; Sivakumar, S.S.; Gunasekar, J.J. Development and evaluation of manually operated plastic mulch and drip laying machine for horticultural crops. *Agric. Eng. Today* **2022**, *46*, 60–63. Available online: https://pub.isae.in/index.php/aet/article/view/3039 (accessed on 1 November 2026).
41. Syromyatnikov, Y.; Khramov, N.; Troyanovskaya, I.; Voinash, S.; Partko, S.; Zagidullin, R. Work quality indicators tillage unit with application flexible working body in systems "Organic farming". *E3S Web Conf.* **2023**, *463*, 01001. https://doi.org/10.1051/e3sconf/202346301001.
42. Dzjasheev, A.M.; Orekhovskaya, A.A.; Taraban, M.V. Substantiation of flat blade parameters for soil loosening. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *981*, 042043. https://doi.org/10.1088/1755-1315/981/4/042043.
43. Tikhonov, E.A.; Luchinovich, A.A.; Bielykh, A.V. Cultivator points of the rotary tillage loosening and separating machine of the stratifier. *J. Phys. Conf. Ser.* **2021**, *2094*, 042024. https://doi.org/10.1088/1742-6596/2094/4/042024.
44. *GOST 28268-89*; Soils. Methods of Determination of Moisture, Maximum Hygroscopic Moisture and Moisture of Steady Plant Fading. Standartinform: Moscow, Russia, 2006. (In Russian)
45. Karadirek, I.E. An experimental analysis on accuracy of customer water meters under various flow rates and water pressures. *J. Water Supply Res. Technol.—AQUA* **2020**, *69*, 18–27. https://doi.org/10.2166/aqua.2019.031.
46. Simões, C.F.; Ribeiro, Á.S.; Almeida, M.C.; Covas, D. Traceability and measurement uncertainty of non-removable field flowmeters using clamp-on ultrasonic flowmeters as reference. *Acta IMEKO* **2024**, *13*, 1–6. https://doi.org/10.21014/actaimeko.v13i3.1777.
47. *GOST 7178-85*; Fresh Melons. Specifications. Standartinform: Moscow, Russia, 2010. (In Russian)
48. Zeilerbauer, L.; Fischer, J.; Fazeni-Fraisl, K.; Mager, M.; Lindorfer, J.; Paulik, C. Life cycle assessment of mechanical recycling of low-density polyethylene into film products—Towards the need for life cycle thinking in product design. *Resour. Conserv. Recycl.* **2024**, *209*, 107807. https://doi.org/10.1016/j.resconrec.2024.107807.
49. Zhang, Q.; Wang, S.; Sun, Y.; Zhang, Y.; Li, H.; Liu, P.; Wang, X.; Wang, R.; Li, J. Conservation tillage improves soil water storage, spring maize (*Zea mays* L.) yield and WUE in two types of seasonal rainfall distributions. *Soil Tillage Res.* **2022**, *215*, 105237. https://doi.org/10.1016/j.still.2021.105237.
50. Bedenko, I.; Sakhapov, R. Influence of cultivation technology on the yield of winter wheat. *E3S Web Conf.* **2023**, *443*, 02001. https://doi.org/10.1051/e3sconf/202344302001.

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