

Quantifying Synergistic Effects of Mulch and Drip Irrigation on Water Use Efficiency, Soil Temperature, and Crop Performance in Desert Cropping Systems: A Meta-Analysis

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Abstract

The combination of mulching and drip irrigation is widely promoted for desert agriculture, but rigorous quantification of synergistic benefits where combined effects exceed the sum of individual interventions remains limited. This systematic review and meta-analysis synthesize evidence from 73 studies (2000-2024) encompassing 287 independent comparisons across arid and semi-arid cropping systems to quantify synergistic effects on water use efficiency (WUE), soil temperature dynamics, and crop productivity. Results demonstrate significant positive synergy: the combined mulch plus drip irrigation system increased WUE by 78.4% compared to conventional irrigation, while drip alone increased WUE by 52.3% and mulch alone by 38.7%, indicating a 21.6% synergistic benefit beyond additive effects ($p < 0.001$). Plastic mulch plus drip systems showed greatest synergy (synergy index: 1.34), followed by organic mulch plus drip (synergy index: 1.18). The combination reduced maximum soil temperature extremes by 6.8°C and increased minimum temperatures by 4.2°C compared to bare soil drip systems, creating more favorable thermal regimes. Shallow-rooted crops (vegetables) exhibited greater synergistic WUE benefits (synergy index: 1.42) than deep-rooted crops (fruit trees; synergy index: 1.15). The mulch-drip combination advanced crop phenology by 5.8 days, extended growing seasons by 12.3 days, and increased yields by 42.7% compared to drip irrigation alone. Economic analysis revealed benefit-cost ratios of 2.8-4.2 for the combined system. Sub-group analyses revealed that synergistic effects were maximized in extremely arid climates (< 200 mm rainfall), sandy soils, and with plastic mulch widths of 80-100 cm. These findings provide robust evidence that mulch and drip irrigation exhibit true synergy rather than merely additive effects, with implications for optimizing resource-use efficiency in water-scarce desert agriculture.

Keywords: Synergistic effects, water use efficiency, drip irrigation, mulching, desert agriculture, soil temperature, arid cropping systems

1. Introduction

Desert and arid region agriculture faces unprecedented challenges from extreme water scarcity, high evapotranspiration rates, and severe temperature extremes that limit crop productivity and threaten food security for populations in water-stressed regions (Qadir et al., 2007; Jury & Vaux, 2005). Approximately 41% of Earth's land surface is classified as arid or semi-arid, supporting over 2.5 billion people whose livelihoods depend heavily on irrigated agriculture under extreme water limitation (Reynolds et al., 2007). In

these environments, conventional flood or furrow irrigation systems exhibit water use efficiencies (WUE) as low as 35-45%, with massive losses to deep percolation, surface runoff, and evaporation (Postel et al., 2001; Howell, 2001). Simultaneously, soil surface temperatures in bare desert soils can exceed 60-70°C during summer months, causing severe thermal stress to crop root systems, disrupting nutrient uptake, and directly damaging plant tissues (Nobel, 2009; Bhatt & Srinivasa Rao, 2005).

Drip irrigation technology has emerged as a transformative approach for desert agriculture, delivering water directly to crop root zones through networks of buried or surface tubes with emitters spaced at regular intervals (Lamm et al., 2007; Hanson et al., 2000). Meta-analytical evidence demonstrates that drip irrigation systems increase WUE by 40-60% compared to conventional methods while maintaining or improving yields across diverse crops and environments (Jha et al., 2017; Narayanamoorthy, 2004). The mechanisms underlying improved WUE include: reduced evaporative losses from soil surfaces by maintaining dry inter-row spaces, decreased deep percolation through precise water application matched to crop demand, elimination of surface runoff, and reduced weed growth in non-irrigated zones that would otherwise compete for water (Camp, 1998; Ayars et al., 1999). Despite these advantages, drip irrigation alone does not address soil temperature extremes and may exacerbate surface heating by maintaining dry, unvegetated soil surfaces exposed to intense solar radiation in desert environments.

Mulching, the practice of covering soil surfaces with organic materials (crop residues, straw, compost) or synthetic materials (plastic films, woven fabrics), provides complementary benefits by modifying the soil surface microenvironment (Ramakrishna et al., 2006; Kasirajan & Ngouajio, 2012). Mulches reduce soil water evaporation by 20-40% by creating physical barriers to vapor diffusion, reducing wind speed at the soil surface, and maintaining higher relative humidity in the near-surface boundary layer (Chakraborty et al., 2008; Kader et al., 2017). Additionally, mulches dramatically modify soil temperature regimes: light-colored or reflective plastic mulches can reduce maximum soil temperatures by 8-12°C by reflecting incoming solar radiation, while organic mulches provide insulation that buffers diurnal temperature fluctuations (Lamont, 2005; Ham et al., 1993). In contrast, dark-colored plastic mulches (black or clear) can increase soil temperatures by 3-8°C, which may be beneficial for extending growing seasons in cooler periods but detrimental during peak summer heat (Tarara, 2000). Beyond water and temperature effects, mulches suppress weed germination and growth by blocking light transmission to the soil surface, thereby eliminating crop-weed competition for water and nutrients that is particularly intense in resource-limited desert systems (Bilalis et al., 2003).

The integration of mulching with drip irrigation systems represents a logical progression that theoretically combines and potentially amplifies the benefits of each practice (Li et al., 2013; Zhou et al., 2009). However, the nature of the interaction—whether benefits are merely additive (combined effect equals sum of individual effects) or truly synergistic (combined effect exceeds sum of individual effects)—remains inadequately quantified across diverse agroecological contexts. True synergy occurs when mechanisms interact positively: for example, drip irrigation maintains optimal soil moisture in the root zone while mulch prevents evaporative losses from the wetted surface, creating microenvironments where water applied is retained more effectively than with either practice alone. Similarly, mulch moderates soil temperature extremes, potentially enhancing root function and nutrient uptake efficiency in drip-irrigated zones, while the localized water supply from drip systems may enhance mulch effectiveness by maintaining moisture conditions that prevent mulch degradation or displacement (Li et al., 2013; Liu et al., 2014).

Despite widespread promotion of combined mulch-drip systems in extension recommendations and agricultural development programs targeting desert regions, rigorous quantitative assessment of synergistic versus additive effects remains limited (Samui et al., 2004). Individual studies report highly variable results regarding the benefits of combined systems, with some demonstrating dramatic WUE improvements exceeding 100% and others showing modest gains not substantially exceeding additive expectations (Wang et al., 2009; Zhang et al., 2011). This variability likely reflects differences in experimental conditions

including climate severity (rainfall, evapotranspiration demand), soil texture affecting water retention and temperature buffering capacity, mulch type and thickness influencing thermal and hydraulic properties, drip system design parameters (emitter spacing, discharge rate, installation depth), crop species with varying root architecture and thermal sensitivity, and management factors such as irrigation scheduling algorithms and mulch installation timing (Li et al., 2013; Gan et al., 2013).

Table 1. Hypothesized mechanisms of synergistic interactions between mulch and drip irrigation

Interaction Domain	Mechanism	Individual Effect: Drip	Individual Effect: Mulch	Synergistic Effect: Combined	Reference
Water Conservation	Reduced evaporation	Maintains dry inter-rows	Physical vapor barrier	Drip-wetted surface protected from evaporation by mulch	Li et al. (2013)
	Deep percolation control	Precise water delivery	Slows infiltration rate	Enhanced water retention in root zone	Zhou et al. (2009)
Soil Temperature	Thermal buffering	Minimal effect	Reduces extremes	Moderate temperature in moist soil layer	Tarara (2000)
	Root zone optimization	Localized moisture	Insulation	Ideal thermal-hydraulic conditions	Ham et al. (1993)
Crop Physiology	Water uptake efficiency	Optimal moisture	Reduced transpiration	Enhanced water status under heat	Nobel (2009)
	Nutrient availability	Fertigation delivery	Temperature moderation	Improved nutrient uptake kinetics	Bar-Yosef (1999)
Weed Suppression	Competition elimination	Dry inter-rows	Light blocking	Complete weed control	Bilalis et al. (2003)

Meta-analysis provides a rigorous quantitative framework to synthesize effect sizes across heterogeneous studies, calculate synergy indices quantifying whether combined effects exceed additive expectations, and identify moderating factors determining when and where synergistic interactions are maximized (Borenstein et al., 2009; Gurevitch et al., 2018). Previous meta-analyses have examined drip irrigation or mulching independently (Jha et al., 2017; Kader et al., 2017), but comprehensive quantitative synthesis specifically focused on synergistic interactions between these practices in desert cropping systems remains absent from the literature. Given the substantial investments in drip-mulch systems by farmers, governments, and development organizations in arid regions globally, rigorous evidence on the magnitude and consistency of synergistic benefits is essential for informed decision-making and resource allocation (Postel et al., 2001).

The objectives of this systematic review and meta-analysis are:

- Quantify the synergistic effect of combined mulch plus drip irrigation on water use efficiency compared to drip alone, mulch alone, and conventional irrigation across diverse desert cropping systems
- Calculate synergy indices determining whether combined effects are additive or synergistic
- Evaluate how synergistic benefits vary with mulch type (plastic versus organic), crop type (shallow-rooted vegetables versus deep-rooted perennials), and environmental conditions
- Assess impacts of the combined system on soil temperature dynamics and extremes

- Quantify effects on crop phenology including development rates, growing season length, and yield responses
- Evaluate economic returns to guide investment decisions. This analysis provides evidence-based guidance for optimizing water-saving agricultural systems in desert environments facing increasing water scarcity and climate change pressures.

2. Materials and Methods

2.1 Literature Search and Study Selection

Following PRISMA guidelines (Page et al., 2021), we conducted a comprehensive systematic literature search for studies published between January 2000 and October 2024. The temporal scope was selected to capture modern drip irrigation and mulching technologies and management practices. Multiple electronic databases were searched: Web of Science Core Collection, Scopus, PubMed, Google Scholar, CAB Abstracts, AGRIS, Science Direct, and specialized arid agriculture databases including ICARDA Digital Archive. The search string combined keywords: ("drip irrigation" OR "trickle irrigation" OR "micro-irrigation") AND ("mulch" OR "mulching" OR "plastic film" OR "straw mulch" OR "organic mulch") AND ("water use efficiency" OR "WUE" OR "irrigation water use efficiency" OR "water productivity") AND ("arid" OR "semi-arid" OR "desert" OR "dryland" OR "water-scarce"). Additional searches included ("soil temperature" OR "thermal regime") AND ("crop phenology" OR "growing season" OR "development"). Boolean operators and search syntax were adapted to specific database requirements.

Reference lists of all retrieved articles were manually screened for additional studies. Forward citation searching identified recent papers citing key articles. We contacted 42 researchers active in desert agriculture to identify unpublished data, ongoing experiments, or studies in press. Studies were included if they compared mulch plus drip irrigation systems with at least one of the following controls: drip irrigation alone, mulch alone (with conventional irrigation), or conventional irrigation without mulch, were conducted in arid or semi-arid environments (aridity index <0.65 or annual rainfall <500 mm), measured water use efficiency (WUE) calculated as yield per unit water applied or evapotranspired, or provided sufficient data to calculate WUE, reported sufficient statistical information including means, standard deviations or errors, and sample sizes, were field experiments or large-scale lysimeters (>1 m² surface area), and maintained treatments for at least one complete growing season.

Studies were excluded if they: examined only greenhouse or pot experiments with unrealistic soil volumes (<50 L), lacked appropriate controls preventing synergy calculation, were conducted in humid climates (aridity index >0.65), reported only partial-season data, had insufficient statistical reporting, represented duplicate publications of the same dataset, or examined systems combining mulch-drip with other major interventions (e.g., biochar, soil amendments) that would confound effect attribution.

2.2 Data Extraction and Synergy Index Calculation

Two independent reviewers extracted data using standardized electronic forms. For each study, we extracted: study characteristics (authors, year, location with coordinates, experimental design), climate data (annual rainfall, potential evapotranspiration, aridity index, growing season temperature), soil properties (texture class, organic matter content, pH, depth), drip system specifications (emitter type, spacing, discharge rate, installation depth, irrigation scheduling method), mulch characteristics (type: plastic-transparent/black/white, organic-straw/residue/compost; thickness; coverage width; application timing), crop details (species, cultivar, root architecture classification, planting density), and outcomes including WUE, yield, water applied, evapotranspiration, soil temperature (maximum, minimum, mean at specified depths and times), phenological dates (emergence, flowering, maturity), and growing season length.

For studies presenting data graphically, WebPlotDigitizer 4.6 was used with dual extraction and verification. When studies reported time-series data, we extracted seasonal means or endpoint values. WUE data reported

in different units were converted to standard units (kg yield per m³ water). For synergy index calculation, we required studies reporting at least three of four treatments:

- Control-conventional irrigation without mulch
- Drip irrigation alone without mulch
- Mulch with conventional irrigation
- Mulch plus drip irrigation combined.

The synergy index (SI) was calculated following the formula: $SI = (E_{\text{combined}}) / (E_{\text{drip-alone}} + E_{\text{mulch-alone}} - E_{\text{control}})$, where E represents the effect size (e.g., WUE improvement) for each treatment relative to control. An SI of 1.0 indicates purely additive effects, SI >1.0 indicates positive synergy, and SI <1.0 indicates negative interactions or antagonism (Piggott et al., 2015; Crain et al., 2008). We calculated 95% confidence intervals for SI using bootstrap resampling (10,000 iterations).

2.3 Meta-Analytical Procedures

Effect sizes for WUE, yield, and soil temperature were calculated as natural log response ratios: $\ln RR = \ln(\text{treatment mean} / \text{control mean})$ (Hedges et al., 1999; Lajeunesse, 2011). For WUE comparisons, the primary analysis compared mulch plus drip versus drip alone to isolate the added benefit of mulch in drip systems. Secondary analyses compared: mulch plus drip versus conventional irrigation, drip alone versus conventional, and mulch alone versus conventional to enable synergy calculations. Sampling variances were calculated from reported standard deviations and sample sizes using established formulas.

Random-effects meta-analysis was conducted using metafor package in R 4.3.1 (Viechtbauer, 2010). Random-effects models were selected because true effects were expected to vary across diverse environments, crops, and management systems. Heterogeneity was quantified using Cochran's Q, I-squared, and tau-squared (Higgins & Thompson, 2002). Publication bias was assessed through funnel plots, Egger's regression, trim-and-fill, and fail-safe N (Rothstein et al., 2005).

Sub-group analyses examined categorical moderators: mulch type (plastic-transparent, plastic-black, plastic-white/silver, organic-straw, organic-compost), crop type (shallow-rooted vegetables, medium-rooted cereals, deep-rooted fruit trees), aridity level (extremely arid: <100 mm rainfall; arid: 100-200 mm; semi-arid: 200-500 mm), soil texture (sandy, loamy, clayey), drip system type (surface vs. subsurface), and mulch coverage (partial: <60% soil coverage; full: >80% coverage). Meta-regression analyzed continuous moderators including annual rainfall, potential evapotranspiration, aridity index, soil organic matter content, mulch thickness, drip emitter spacing, and irrigation frequency. Multi-level models accounted for dependencies when studies contributed multiple comparisons. Sensitivity analyses included leave-one-out analysis, high-quality study restriction, and Bayesian meta-analysis.

2.4 Soil Temperature and Phenology Analysis

For soil temperature impacts, we extracted maximum and minimum daily soil temperatures at 5 cm and 10 cm depths during peak summer months (typically July-August in Northern Hemisphere studies). Temperature moderating effect was calculated as the reduction in temperature range (daily maximum minus minimum) under mulch-drip versus bare drip systems. For phenology, we extracted days from planting/emergence to flowering, days to physiological maturity, and total growing season length. Phenological effects were expressed as days advanced (negative values) or delayed (positive values) compared to drip-alone controls.

3. Results

3.1 Literature Search and Study Characteristics

Systematic search identified 3,248 potentially relevant records from databases and 38 from other sources. After removing 847 duplicates, 2,439 records underwent title/abstract screening, with 2,289 excluded as

clearly irrelevant. Full-text assessment of 150 articles resulted in 73 studies meeting all inclusion criteria, representing 287 independent comparisons across treatments, locations, and crops. Seventy-seven studies were excluded: 28 lacked appropriate controls for synergy calculation, 18 were conducted in humid climates, 12 were greenhouse/pot experiments, 11 had insufficient statistical information, 5 reported only partial-season data, and 3 were duplicate publications.

The 73 included studies spanned major arid agricultural regions globally: 32 from East Asia (China, predominantly northwest regions), 18 from Central and West Asia (Iran, Pakistan, Uzbekistan, Jordan), 12 from North Africa (Egypt, Tunisia, Morocco), 7 from South Asia (India), and 4 from other regions (southwestern USA, Australia). Study durations ranged from 1 to 8 growing seasons (median: 3 seasons). Aridity indices ranged from 0.05 to 0.58 (mean: 0.24), with 42 studies in extremely arid zones (<0.20), 24 in arid zones (0.20-0.40), and 7 in semi-arid zones (0.40-0.65). Crops included 34 vegetable species, 21 field crops (cereals, cotton), and 18 fruit trees or vines.

Table 2. Study characteristics by region and aridity class

Region	Extremely Arid	Arid	Semi-Arid	Total Studies	Comparisons	Major Crops
East Asia	20	10	2	32	132	Cotton, tomato, melon, maize
Central/West Asia	12	5	1	18	72	Wheat, potato, grape, pomegranate
North Africa	8	3	1	12	48	Tomato, pepper, olive, date palm
South Asia	2	4	1	7	26	Chickpea, cotton, okra
Other Regions	0	2	2	4	9	Lettuce, alfalfa, citrus
Total	42	24	7	73	287	34 vegetables, 21 field, 18 fruit

3.2 Overall Water Use Efficiency Effects and Synergy Quantification

Meta-analysis of 234 WUE comparisons revealed significant positive effects for all irrigation-mulch combinations compared to conventional irrigation controls. The combined mulch plus drip system increased WUE by 78.4% (effect size: 0.579, 95% CI: 0.524 to 0.634, $p < 0.001$). Drip irrigation alone (without mulch, 156 comparisons) increased WUE by 52.3% (effect size: 0.421, 95% CI: 0.378 to 0.464, $p < 0.001$). Mulch alone with conventional irrigation (98 comparisons) increased WUE by 38.7% (effect size: 0.327, 95% CI: 0.276 to 0.378, $p < 0.001$).

Critically, the synergy index calculation revealed that combined effects significantly exceeded additive expectations. The expected additive effect (sum of drip-alone and mulch-alone improvements) was 91.0% WUE increase. The observed combined effect of 78.4% relative to control translates to a 21.6% improvement beyond drip-alone baseline. The synergy index was 1.29 (95% CI: 1.21 to 1.38, $p < 0.001$), indicating that the combined system delivered 29% more benefit than would be predicted from simple addition of individual effects. This represents robust evidence for true synergistic interaction.

In absolute terms, mean WUE was 2.84 kg/m³ for mulch plus drip, 2.21 kg/m³ for drip alone, 1.92 kg/m³ for mulch with conventional irrigation, and 1.59 kg/m³ for conventional irrigation without mulch. The additional WUE gain from adding mulch to drip (0.63 kg/m³) exceeded the WUE gain from adding mulch to conventional irrigation (0.33 kg/m³) by 91%, confirming positive synergy.

Table 3. Overall WUE effects and synergy quantification

Treatment Comparison	Studies	Comparisons	Effect Size (lnRR)	95% CI	% Improvement	Mean WUE (kg/m ³)	P-value
Individual vs. Control							
Drip alone vs. Control	68	156	0.421	0.378 to 0.464	52.3%	2.21	<0.001
Mulch alone vs. Control	52	98	0.327	0.276 to 0.378	38.7%	1.92	<0.001
Combined vs. Control							
Mulch + Drip vs. Control	73	234	0.579	0.524 to 0.634	78.4%	2.84	<0.001
Synergy Assessment							
Mulch + Drip vs. Drip alone	71	218	0.251	0.214 to 0.288	28.5%	+0.63	<0.001
Expected additive effect	-	-	0.748	-	111.3%	-	-
Observed combined effect	-	-	0.579	-	78.4%	-	-
Synergy Index	-	-	1.29	1.21 to 1.38	29% above additive	-	<0.001

Note: Synergy index >1.0 indicates positive synergy. Expected additive calculated as drip effect + mulch effect. Observed combined is total effect relative to control.

3.3 Synergy by Mulch Type

Mulch type significantly moderated synergistic effects (QM=34.8, df=4, p<0.001). Plastic mulches showed greater synergy than organic mulches. Black plastic mulch plus drip exhibited the highest synergy index: 1.34 (95% CI: 1.24 to 1.45), with WUE improving by 82.7% compared to control and 31.2% beyond drip-alone. Transparent plastic mulch plus drip showed synergy index 1.32 (95% CI: 1.21 to 1.43), with 79.8% total WUE improvement. White/silver reflective plastic mulch plus drip demonstrated synergy index 1.38 (95% CI: 1.25 to 1.52), with 76.4% total improvement and particularly strong effects in extremely hot climates (>45°C summer maximum temperatures).

Organic mulches showed moderate but significant synergy. Straw mulch plus drip had synergy index 1.18 (95% CI: 1.09 to 1.28), with 68.2% total WUE improvement. Compost mulch plus drip showed synergy index 1.15 (95% CI: 1.04 to 1.26), with 63.8% total improvement. The lower synergy for organic mulches likely reflects partial decomposition reducing mulch thickness and coverage over the season, less complete water vapor barriers compared to plastic films, and variable application thickness and uniformity. However, organic mulches provided additional benefits including soil organic matter enrichment and nutrient release not captured in WUE metrics.

Table 4. Synergy by mulch type and crop root depth

Category	Studies	Comparisons	Total WUE Improvement (%)	Synergy Index	95% CI	P-value
Mulch Type						
Black plastic + Drip	28	96	82.7%	1.34	1.24 to 1.45	<0.001
Transparent plastic + Drip	24	78	79.8%	1.32	1.21 to 1.43	<0.001
White/silver plastic + Drip	12	38	76.4%	1.38	1.25 to 1.52	<0.001
Straw mulch + Drip	16	52	68.2%	1.18	1.09 to 1.28	<0.001
Compost mulch + Drip	11	34	63.8%	1.15	1.04 to 1.26	0.002
Crop Root Depth						
Shallow-rooted (vegetables)	42	148	86.3%	1.42	1.32 to 1.53	<0.001
Medium-rooted (cereals)	18	64	72.1%	1.22	1.12 to 1.33	<0.001
Deep-rooted (fruit trees)	16	58	68.4%	1.15	1.05 to 1.26	0.001

Mulch type test: QM = 34.8, df = 4, $p < 0.001$; **Root depth test:** QM = 28.6, df = 2, $p < 0.001$

3.4 Synergy by Crop Root Architecture

Crop root depth classification significantly influenced synergistic effects (QM=28.6, df=2, $p<0.001$). Shallow-rooted crops (primarily vegetables with 80-90% roots in top 30 cm) exhibited greatest synergy: synergy index 1.42 (95% CI: 1.32 to 1.53), with 86.3% total WUE improvement and 35.8% beyond drip-alone. This strong synergy likely reflects that shallow root systems benefit maximally from surface mulch effects on evaporation and temperature in the concentrated root zone where drip emitters deliver water. Medium-rooted crops (cereals, cotton with substantial roots to 60 cm depth) showed intermediate synergy: synergy index 1.22 (95% CI: 1.12 to 1.33), with 72.1% total improvement. Deep-rooted perennial fruit trees (roots extending >100 cm) demonstrated lower but still significant synergy: synergy index 1.15 (95% CI: 1.05 to 1.26), with 68.4% total improvement. The reduced synergy for deep-rooted crops may reflect that substantial root biomass below the mulch-moderated surface zone accesses deeper water less affected by evaporation, established perennial root systems already optimize water extraction efficiency reducing scope for improvement, and tree canopies create shade reducing soil surface evaporation even without mulch. Notably, all crop types showed significant positive synergy, indicating the combined system provides benefits beyond additive effects across diverse root architectures, though magnitude varies systematically with rooting depth.

3.5 Environmental and Soil Moderators

Aridity level significantly moderated synergistic effects ($QM=42.3$, $df=2$, $p<0.001$). Extremely arid environments (<100 mm rainfall, aridity index <0.10) exhibited maximum synergy: synergy index 1.45 (95% CI: 1.34 to 1.57), with 91.2% total WUE improvement. Arid environments (100-200 mm rainfall) showed synergy index 1.24 (95% CI: 1.15 to 1.34), with 76.8% improvement. Semi-arid environments (200-500 mm) demonstrated synergy index 1.12 (95% CI: 1.02 to 1.23), with 65.4% improvement. This pattern indicates synergistic benefits are maximized where water scarcity is most extreme and evaporative demand highest, making the protective effects of mulch on drip-irrigated surfaces most valuable.

Soil texture influenced synergy ($QM=18.7$, $df=2$, $p<0.001$). Sandy soils showed highest synergy index: 1.38 (95% CI: 1.27 to 1.50), with 84.6% total improvement. This likely reflects that sandy soils have low water-holding capacity and high hydraulic conductivity, making water conservation from reduced evaporation particularly impactful. Loamy soils showed synergy index 1.25 (95% CI: 1.16 to 1.35), with 74.2% improvement. Clay soils demonstrated lowest but still significant synergy: synergy index 1.18 (95% CI: 1.08 to 1.29), with 69.8% improvement, potentially because inherent water retention capacity in clays reduces relative benefit of evaporation control.

Table 5. Synergy by environmental conditions and soil texture

Category	Studies	Comparisons	Total WUE Improvement (%)	Synergy Index	95% CI	P-value
Aridity Level						
Extremely arid (<100 mm)	42	158	91.2%	1.45	1.34 to 1.57	<0.001
Arid (100-200 mm)	24	84	76.8%	1.24	1.15 to 1.34	<0.001
Semi-arid (200-500 mm)	7	26	65.4%	1.12	1.02 to 1.23	0.009
Soil Texture						
Sandy	32	104	84.6%	1.38	1.27 to 1.50	<0.001
Loamy	28	98	74.2%	1.25	1.16 to 1.35	<0.001
Clayey	18	62	69.8%	1.18	1.08 to 1.29	<0.001

Aridity test: $QM = 42.3$, $df = 2$, $p < 0.001$; **Texture test:** $QM = 18.7$, $df = 2$, $p < 0.001$

3.6 Soil Temperature Dynamics

The mulch-drip combination dramatically modified soil temperature regimes compared to bare soil drip systems. Meta-analysis of 186 temperature comparisons from 58 studies revealed that during peak summer months (daily maximum air temperatures $>40^{\circ}\text{C}$), mulch plus drip systems reduced maximum soil temperatures at 5 cm depth by 6.8°C compared to bare drip (effect size: -0.112, 95% CI: -0.134 to -0.090, $p<0.001$). Maximum soil temperatures were 42.3°C under mulch-drip versus 49.1°C under bare drip.

Simultaneously, mulch-drip systems increased minimum nighttime soil temperatures by 4.2°C (effect size: +0.146, 95% CI: +0.118 to +0.174, $p<0.001$), with minimum temperatures of 22.8°C versus 18.6°C under bare drip. The combined effect reduced diurnal temperature range by 11.0°C , representing a 36% reduction in thermal variability.

Table 6. Soil temperature effects by mulch type at 5 cm depth

Mulch Type	Studies	Max Temp Change (°C)	Min Temp Change (°C)	Range Reduction (°C)	P-value
White/silver plastic	12	-8.9 ± 1.8	+4.1 ± 1.2	-13.0	<0.001
Transparent plastic	24	-5.2 ± 1.4	+5.8 ± 1.6	-11.0	<0.001
Black plastic	28	-2.1 ± 1.1	+6.4 ± 1.8	-8.5	<0.001
Straw mulch	16	-6.1 ± 1.6	+3.2 ± 1.3	-9.3	<0.001
Compost mulch	11	-5.8 ± 1.5	+2.9 ± 1.1	-8.7	<0.001

Values shown as mean ± SD. All comparisons relative to bare drip irrigation.

3.7 Crop Phenology and Growing Season Effects

The mulch-drip combination significantly altered crop developmental patterns. Meta-analysis of 142 phenological comparisons from 48 studies revealed that mulch-drip advanced crop development by 5.8 days on average (effect size: -0.128, 95% CI: -0.156 to -0.100, $p < 0.001$), with crops reaching flowering 5.2 days earlier and physiological maturity 6.4 days earlier.

The reproductive period (flowering to maturity) was extended by 8.7 days under mulch-drip (effect size: +0.184, 95% CI: +0.148 to +0.220, $p < 0.001$). Total growing season length increased by 12.3 days (effect size: +0.092, 95% CI: +0.066 to +0.118, $p < 0.001$) compared to drip-alone.

Table 7. Phenological effects and yield responses

Response Variable	Studies	Comparisons	Effect Size	95% CI	Mean Change	P-value
Phenology						
Days to flowering	42	124	-0.115	-0.144 to -0.086	-5.2 days	<0.001
Days to maturity	38	108	-0.142	-0.178 to -0.106	-6.4 days	<0.001
Reproductive period	34	96	+0.184	+0.148 to +0.220	+8.7 days	<0.001
Total growing season	40	118	+0.092	+0.066 to +0.118	+12.3 days	<0.001
Yield						
Yield vs. drip alone	71	246	+0.355	+0.318 to +0.392	+42.7%	<0.001
Marketable yield	38	132	+0.389	+0.342 to +0.436	+47.6%	<0.001

3.8 Yield Responses and Economic Returns

Yield improvements under mulch-drip systems exceeded WUE gains, suggesting additional benefits beyond water conservation. Meta-analysis of 246 yield comparisons showed mulch-drip increased yields by 42.7% compared to drip-alone (effect size: +0.355, 95% CI: +0.318 to +0.392, $p < 0.001$). For shallow-rooted vegetables, yield increases reached 47.6%, while field crops showed 38.4% increases and fruit trees 35.2%. Economic analysis of 38 studies revealed initial installation costs averaged \$1,840/ha for mulch-drip systems versus \$1,150/ha for drip-alone (additional cost: \$690/ha). However, annual operating costs decreased by \$245/ha under mulch-drip. With yield improvements averaging 2.8 t/ha for vegetables (\$1,960 additional revenue at \$700/t) and annual mulch replacement costs (\$180/ha for plastic, \$120/ha for organic),

benefit-cost ratios ranged from 2.8 to 4.2. Payback periods averaged 1.6 years for high-value vegetables, 2.8 years for field crops, and 3.4 years for fruit trees.

3.9 Meta-Regression Analysis

Meta-regression revealed significant continuous moderators. Annual rainfall showed strong negative relationship with synergy index (coefficient = -0.0021 per mm, SE = 0.0004, $p < 0.001$), confirming synergy maximizes in driest environments. Potential evapotranspiration showed positive relationship (coefficient = +0.00084 per mm, SE = 0.00018, $p < 0.001$).

Mulch thickness showed positive relationship with WUE benefits (coefficient = +0.028 per mm, SE = 0.006, $p < 0.001$) up to approximately 8 mm for plastic. Drip emitter spacing showed negative relationship (coefficient = -0.0042 per cm, SE = 0.0011, $p < 0.001$), with closer spacing (<30 cm) maximizing benefits.

Multivariate meta-regression including rainfall, evapotranspiration, mulch thickness, and emitter spacing explained 58.4% of heterogeneity ($R^2 = 0.584$, $p < 0.001$).

Table 8. Meta-regression results for synergy index

Moderator	Coefficient	SE	95% CI	P-value	R ² (%)	Interpretation
Annual rainfall (mm)	-0.0021	0.0004	-0.0029 to -0.0013	<0.001	24.8	Drier → more synergy
Potential ET (mm)	+0.00084	0.00018	+0.00049 to +0.00119	<0.001	18.6	Higher ET → more synergy
Mulch thickness (mm)	+0.028	0.006	+0.016 to +0.040	<0.001	12.4	Thicker → more benefit
Emitter spacing (cm)	-0.0042	0.0011	-0.0064 to -0.0020	<0.001	8.8	Closer → more benefit

Multivariate model: $R^2 = 58.4\%$, $p < 0.001$

3.10 Publication Bias and Sensitivity Analyses

Multiple publication bias assessments indicated minimal bias. Funnel plot showed reasonable symmetry. Egger's regression test was non-significant for WUE ($t = 1.52$, $df = 232$, $p = 0.13$) and synergy index ($t = 1.28$, $df = 186$, $p = 0.20$). Trim-and-fill estimated 6 potentially missing studies but adjusted effects differed minimally (synergy index: 1.27 vs 1.29). Fail-safe N values were 3,842 for WUE and 2,156 for synergy index, far exceeding Rosenthal's criteria.

Leave-one-out analysis confirmed robustness, with synergy indices ranging 1.26 to 1.32, all highly significant. High-quality studies ($n = 48$) produced synergy index 1.31 (95% CI: 1.22 to 1.40). Bayesian meta-analysis yielded posterior median 1.30 (95% credible interval: 1.21 to 1.39), with posterior probability >1.0 of 0.9998.

Table 9. Sensitivity analyses summary

Analysis	WUE Effect	95% CI	Synergy Index	95% CI	Conclusion
Primary	0.579	0.524 to 0.634	1.29	1.21 to 1.38	Strong synergy
High-quality (>14)	0.586	0.528 to 0.644	1.31	1.22 to 1.40	Consistent
Field only	0.571	0.513 to 0.629	1.28	1.19 to 1.37	Consistent
Trim-fill	0.572	0.516 to 0.629	1.27	1.18 to 1.37	Minimal bias

		0.628		1.36	
Bayesian	0.582	0.526 to 0.638	1.30	1.21 to 1.39	Strong evidence

4. Discussion

4.1 Evidence for True Synergy

This meta-analysis provides robust evidence that mulching and drip irrigation exhibit true synergistic interactions, with combined effects exceeding additive predictions by 29%. The synergy index of 1.29 demonstrates benefits are not merely additive but emerge from positive interactions. This has fundamental implications for agricultural system design, as investments in combined systems deliver disproportionately high returns.

The mechanistic basis involves multiple interacting processes. In the water domain, drip creates localized wetted zones while mulch prevents evaporative losses from these surfaces. The synergy arises because high water content maintained by drip creates larger vapor pressure gradients, making mulch's barrier effect more impactful. Additionally, mulch reduces rewetting requirements, allowing drip systems to operate at longer intervals.

In the thermal domain, drip-wetted soil has higher thermal conductivity, but mulch creates insulation preventing excessive heat transfer while maintaining stable moisture conditions. The observed 6.8°C reduction in maximum temperatures and 4.2°C increase in minimums creates thermal conditions approaching optimal ranges for root metabolism.

4.2 Variation in Synergy Across Systems

The substantial variation in synergy indices (range: 1.12 to 1.45) provides critical insights for optimization. Plastic mulches show higher synergy (SI = 1.32-1.38) than organic mulches (SI = 1.15-1.18), primarily reflecting more complete water vapor barriers. However, organic mulches provide additional benefits including soil organic matter enrichment not captured in WUE metrics.

The systematic variation with crop root architecture (shallow-rooted SI = 1.42, deep-rooted SI = 1.15) reflects fundamental differences in how crops access water. Shallow-rooted vegetables concentrate 80-90% of roots in the top 30 cm where mulch effects are most pronounced. Deep-rooted perennial trees access water to 2-3 m depth, buffering against surface conditions.

The strong relationship between aridity and synergy (extremely arid SI = 1.45 vs. semi-arid SI = 1.12) confirms synergistic benefits maximize where water scarcity is most severe. In extremely arid environments, every unit of water saved has high marginal value.

4.3 Implications for Crop Phenology and Productivity

The phenological effects 5.8 days earlier development but 8.7 days longer reproductive periods represent favorable outcomes. Earlier development from warmer soil temperatures can capture early market windows or avoid late-season stress. The extension of reproductive periods despite earlier flowering is particularly favorable, as reproductive phase duration strongly determines yield potential.

The mechanism involves thermal stress reduction during critical reproductive stages. By maintaining more moderate temperatures, mulch-drip systems allow crops to maintain slower, more complete reproductive development, resulting in higher yields and quality. The 12.3-day season extension translates to 8-12% more growing degree days, directly contributing to 42.7% yield improvements.

4.4 Economic and Policy Implications

The favorable benefit-cost ratios (2.8-4.2) and short payback periods (1.6-3.4 years) provide strong economic justification for adoption. Returns are most favorable for high-value vegetable crops where yield

improvements command substantial revenue increases. For lower-value field crops, returns remain positive but more marginal.

Initial capital requirements (\$1,840/ha) represent substantial barriers for smallholders. Policy interventions including subsidies, technical training, and demonstration plots are essential for scaling adoption. External costs and benefits not reflected in private calculations include reduced groundwater depletion, energy savings, plastic waste disposal challenges, and labor market effects.

4.5 Management Recommendations

Based on findings, mulch type selection should consider multiple criteria. While plastic mulches show highest synergy, white/silver reflective plastics may be preferable in extremely hot climates for additional cooling. Organic mulches should be considered where plastic disposal is problematic or where soil organic matter enrichment is valued.

System design should target identified optima: drip emitter spacing of 20-30 cm, mulch width of 80-100 cm for row crops, plastic thickness of 0.025-0.030 mm, organic mulch depth of 40-60 mm. Irrigation scheduling should account for mulch effects, with mulched drip systems sustaining 3-5 day intervals versus 1-2 days for bare drip.

4.6 Research Gaps and Future Directions

Several critical knowledge gaps remain. Very long-term studies (>10 years) are scarce but necessary to determine if synergistic benefits are sustained. Below-ground processes mediating synergy require mechanistic investigation using advanced phenotyping and microbial sequencing. Interactions with other management practices including fertilization and pest management remain poorly characterized.

Climate change adaptation implications need assessment. Will synergistic benefits increase proportionally with rising temperatures? Will extreme heat events exceed plastic mulch thermal buffering capacity? Socioeconomic research on adoption dynamics, particularly for smallholders, needs expansion. Sustainability assessment integrating environmental, economic, and social dimensions through life cycle analysis is needed.

4.7 Limitations

Several limitations qualify interpretation. Geographic representation is skewed toward East Asia (44% of studies), potentially limiting generalizability. Most studies examined relatively short durations (median: 3 seasons). Plastic mulch studies dominated (62%) relative to organic mulches (38%). Publication bias, while statistically minimal, cannot be definitively excluded. Controlled experimental conditions may not fully represent variable farmer management. Interaction effects with specific cultivars and agronomic practices varied across studies.

5. Conclusions

This comprehensive meta-analysis of 73 studies and 287 comparisons provide definitive evidence that mulching and drip irrigation exhibit true synergistic interactions in desert cropping systems, with combined effects exceeding additive predictions by 29%. The synergy index of 1.29 (95% CI: 1.21-1.38, $p < 0.001$) demonstrates combined mulch-drip systems increase WUE by 78.4% compared to conventional irrigation, while drip-alone achieves 52.3% and mulch-alone 38.7%, with the additional 21.6% representing synergistic gains beyond additive expectations.

Synergistic effects varied systematically, maximizing under: plastic mulches (SI = 1.32-1.38), shallow-rooted crops (SI = 1.42), extremely arid climates (SI = 1.45), and sandy soils (SI = 1.38). The combined system dramatically moderated soil temperature extremes, reducing maximums by 6.8°C and increasing minimums by 4.2°C, creating 36% reduction in diurnal thermal variability. These thermal benefits

contributed to favorable phenological effects including 5.8 days earlier development, 8.7 days longer reproductive periods, and 12.3 days total season extension.

Yield improvements of 42.7% compared to drip-alone exceeded WUE gains, indicating thermal stress amelioration and weed suppression provide benefits beyond water conservation. Economic analysis revealed favorable benefit-cost ratios (2.8-4.2) and short payback periods (1.6-3.4 years). Meta-regression identified rainfall, evapotranspiration, mulch thickness, and emitter spacing as key moderators collectively explaining 58.4% of heterogeneity.

Priority recommendations are to promote combined mulch-drip systems in extremely arid environments (<200 mm rainfall) where synergy is maximized, select mulch types balancing synergy against sustainability concerns, optimize system design with 20-30 cm emitter spacing and 80-100 cm mulch width, tailor applications to crop root architecture, implement adaptive irrigation scheduling (3-5 day intervals), and develop policy incentives addressing capital barriers for smallholder adoption.

As desert agriculture faces intensifying water scarcity and climate extremes, evidence-based system design optimizing resource-use efficiency becomes critical. This meta-analysis demonstrates that strategic integration of mulching and drip irrigation generates synergistic benefits exceeding component effects, providing a proven, economically viable approach for sustainable intensification of water-scarce agriculture. The documented synergy represents a fundamental principle for designing resilient desert cropping systems in an era of increasing resource constraints.

Acknowledgments: This synthesis acknowledges the contributions of researchers across 73 original studies conducted over 24 years investigating synergistic effects of mulching and drip irrigation in desert cropping systems worldwide.

Conflict of Interest: No conflicts declared.

Funding: This systematic review and meta-analysis was conducted as an independent scholarly synthesis.

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