frontiers | Frontiers in Agronomy

TYPE Original Research
PUBLISHED 11 November 2025
DOI 10.3389/fagro.2025.1663633

Check for updates

OPEN ACCESS

EDITED BY
Yidi Sun,
Yangzhou University, China

REVIEWED BY
Davide Farruggia,
University of Palermo, Italy
Awouminassi Marcellin Atakoun,
University of Parakou, Benin

*CORRESPONDENCE
Richard Solórzano
investigacion_labsaf@inia.gob.pe

RECEIVED 10 July 2025
ACCEPTED 22 October 2025
PUBLISHED 11 November 2025

CITATION
Poma-Chamana R, Cama-Moreno E, Flores-Marquez R, Quello A and Solórzano R (2025) Evaluating soil cover strategies for enhancing water conservation, biomass contribution, and weed control in rocoto pepper (*Capsicum pubescens* Ruiz & Pav.) cultivation under arid conditions. *Front. Agron.* 7:1663633. doi: 10.3389/fagro.2025.1663633

Evaluating soil cover strategies for enhancing water conservation, biomass contribution, and weed control in rocoto pepper (*Capsicum pubescens* Ruiz & Pav.) cultivation under arid conditions

Russell Poma-Chamana[1], Elick Cama-Moreno[1], Ricardo Flores-Marquez[2], Antony Quello[1] and Richard Solórzano[2,3*]

[1]Dirección de Servicios Estratégicos Agrarios, Estación Experimental Agraria de Arequipa, Instituto Nacional de Innovación Agraria (INIA), Arequipa, Peru, [2]Dirección de Servicios Estratégicos Agrarios, Instituto Nacional de Innovación Agraria (INIA), Lima, Peru, [3]Facultad de Ciencias Ambientales, Universidad Científica del Sur (UCSUR), Lima, Peru

Sustainable crop production in arid regions is challenged by soil moisture loss, low organic matter content, and intense weed competition. This study aimed to assess the impact of different mulching strategies on the main crop yield, soil moisture conservation, the contribution of dry biomass and nitrogen to the soil by living covers, and the efficacy of weed control. The experiment was conducted in Santa Rita de Siguas (Arequipa, Peru) using a completely randomized block design with four treatments and three replicates. Measurements included biometric and physiological parameters of rocoto pepper (*Capsicum pubescens*), volumetric soil moisture, dry biomass, and nitrogen content in living covers, as well as weed density. Results indicated that most treatments had no significant impact on the biometric and physiological parameters of rocoto. Plastic mulch reduced irrigation demand and suppressed weeds, although crop yield did not significantly differ among treatments. Among the living mulches, *Trifolium pratense* was more effective than *Melilotus albus* in conserving soil moisture, maintaining levels up to 15.86%. In contrast, *Melilotus albus* produced the highest above-ground dry biomass (8.57 $t{\cdot}h^{-1}$), although both legume species accumulated similar amounts of nitrogen in their biomass. Both living covers gradually reduced weed populations, though without complete eradication. In conclusion, plastic mulch represents a potential option under conditions of severe water limitation. Meanwhile, leguminous cover crops, particularly *M. albus*, offer an alternative complementary strategy for enhancing soil organic matter and could promote long-term sustainability of the cropping system. These findings warrant extended temporal validation to confirm their reproducibility and reliability.

KEYWORDS

living covers, weed control, sustainable agriculture, arid environments, melilotus albus, trifolium pratense

1 Introduction

The rocoto pepper (*Capsicum pubescens* Ruiz & Pav.) is one of the five domesticated species within the *Capsicum* genus. It is native to the arid regions of the Peruvian-Bolivian Andes and later expanded into tropical regions (Walsh and Hoot, 2001). Peru holds the greatest genetic diversity of this species, with 712 preserved accessions, 299 of which belong to *C. pubescens*. Many of these are conserved at the Arequipa Agrarian Experimental Station (Libreros et al., 2013). These accessions are classified into two primary genotypes, *serrano* and *monte*, which are distinguished by differences in fruit size and pungency (Hernández-Amasifuen et al., 2022). Among the *monte* accessions, the red rocoto is particularly notable for its commercial significance in Peru, with an annual production of up to 54,000 tons, 80% of which is concentrated in the central jungle, especially in the Pasco department (MIDAGRI, 2022; Lozano Alarcón, 2012).

In the Arequipa region, the consumption of red rocoto is particularly significant, as it serves as the main ingredient in the traditional dish 'rocoto relleno' and various other culinary preparations (Fuentes and del, 2014; Blanco de Alvarado-Ortiz, 2016). However, the *monte* red rocoto is not commercially cultivated in this region, despite similar temperature ranges between the province of Oxapampa, the main rocoto-producing area, and the province of Arequipa. Historical average temperatures range from a maximum of 24.78°C and a minimum of 13.55°C in Oxapampa to a maximum of 32.2°C and a minimum of 9°C in Santa Rita de Siguas, Arequipa (SENAMHI - Descarga de Datos).

Agriculture in arid regions is subject to severe water limitations. In Arequipa, 25,942 hectares out of 146,824 hectares of agricultural land are located in arid zones, including Majes (15,932 ha), Santa Rita de Siguas (3,032 ha), and La Joya (6,978 ha), all of which rely exclusively on irrigation (Superficie Agrícola). This dependence results in critical water constraints, particularly in the Majes irrigation system, where high water-demand crops contribute to recurrent water deficits (Zapana Churata, 2018). The situation is further exacerbated by inefficient water management, which leads to low irrigation efficiency and substantial water losses through deep infiltration (Wei et al., 2021). Additionally, these arid areas present low organic matter content and reduced water retention capacity (Weil and Brady, 2017) However, proper irrigation management has the potential to increase soil organic carbon (Trost et al., 2013) and improve the cation exchange capacity of coarse-textured soils (Weil and Brady, 2017). These challenges highlight the need to evaluate agronomic strategies, such as mulching use, to optimize water management and organic carbon sequestration in rocoto pepper production in Arequipa.

Mulching involves covering the soil surface with organic or inorganic materials to improve soil properties and optimize crop development (Mulching (Ac.) (484) Conservation Practice Standard | Natural Resources Conservation Service). This practice increases soil organic matter, reduces bulk density, enhances aggregate stability, increases water retention, and regulates soil temperature (Mulching (Ac.) (484) Conservation Practice Standard | Natural Resources Conservation Service; Alyokhin et al., 2019). Additionally, mulching can contribute to pest control and increase crop yields (Cai et al., 2022; Muhammad et al., 2022). Plastic mulch is particularly effective in reducing soil evaporation, increasing soil temperature, and providing efficient weed control (Sokombela et al., 2025), whereas living mulches promote soil biological activity and enhance nutrient availability through the decomposition of plant biomass (Kołota and Adamczewska-Sowińska, 2013). Leguminous cover crops are particularly valuable for their ability to fix atmospheric nitrogen, enrich the soil with high-quality organic matter, and improve nutrient cycling and water retention (Stagnari et al., 2017).

Trifolium pratense L. and *Melilotus albus* Medik exhibit high agronomic potential. *T. pratense* is a perennial species native to temperate regions, characterized by variable root architecture. Erect plants develop deep main roots, whereas low-growing forms produce branched root systems with secondary roots near the stem base (Taylor and Quesenberry, 1996), thereby optimizing water uptake based on the distribution of soil moisture. Commercial cultivars typically produce greater biomass than wild types (Heslop et al., 2025) and have a high nitrogen fixation capacity, reaching up to 545 kg N·ha^{-1}·year^{-1}, along with notable weed control potential (Guntli et al., 1999; Anglade et al., 2015). *M. albus* is an annual or biennial species with erect stems ranging from

30 to 180 cm, capable of producing substantial above-ground biomass (12 t·ha^{-1} of dry matter), making it a promising candidate for restoring degraded soils (Ţîţei, 2022). This species is well-adapted to saline grasslands and arid environments, although its ecology remains largely unexplored (Zabala et al., 2018; Wang et al., 2024), and it has demonstrated adaptability to the desert conditions of Arequipa (Quipuscoa Silvestre et al., 2016).

The application of mulching in rocoto (*Capsicum pubescens*) cultivation remains poorly researched. In related *Capsicum* species, live mulching with *Trifolium pratense* has been shown to provide superior soil moisture retention under water-stress conditions compared to conventional tillage (Biazzo and Masiunas, 2000). Meanwhile, plastic mulch has significantly increased yields under arid conditions (Odokonyero et al., 2025). In this regard, no studies have directly compared the effects of plastic mulching and leguminous living mulches on this crop in Peru, despite the economic importance of rocoto peppers and the cultivation challenges posed by arid regions. This gap proves particularly significant given the dual need to optimize water use while enhancing soil carbon sequestration in these environments. Within this context, the present study aims to evaluate the impact of different mulching strategies (plastic mulching versus leguminous living mulches) on crop yield, soil moisture conservation, dry biomass and nitrogen inputs to soil, as well as weed control in rocoto pepper cultivation under arid conditions.

2 Materials and methods

2.1 Study area

The study was conducted at the Arequipa Agrarian Experimental Station of the National Institute for Agrarian Innovation (INIA), located in the district of Santa Rita de Siguas, province and department of Arequipa, Peru. The experimental plot was situated at 16°28′22.0″ S, 72°06′35.9″ W, at 1,274.28 m.a.s.l. (Figure 1). The region experiences an average annual rainfall of 0.11 mm, with minimum temperatures of 9.3°C in July and maximum temperatures ranging from 25 to 26°C between September and April. These values were calculated based on historical records (1949–2013) of the Majes weather station (16°20′8.4″ S, 72°9′8.92″ W), managed by the National Service of Meteorology and Hydrology of Peru (SENAMHI) (SENAMHI - Descarga de Datos). Additionally, meteorological data were obtained during the experimental period from the Santa Rita weather station, also operated by SENAMHI (Figure 2).

2.2 Experimental design

The experiment was arranged in a randomized complete block design (RCBD) with four treatments and three replicates, resulting in a total of 12 experimental units, each measuring 6 × 5 m, with 1m-wide alleys separating the blocks. The planting layout,

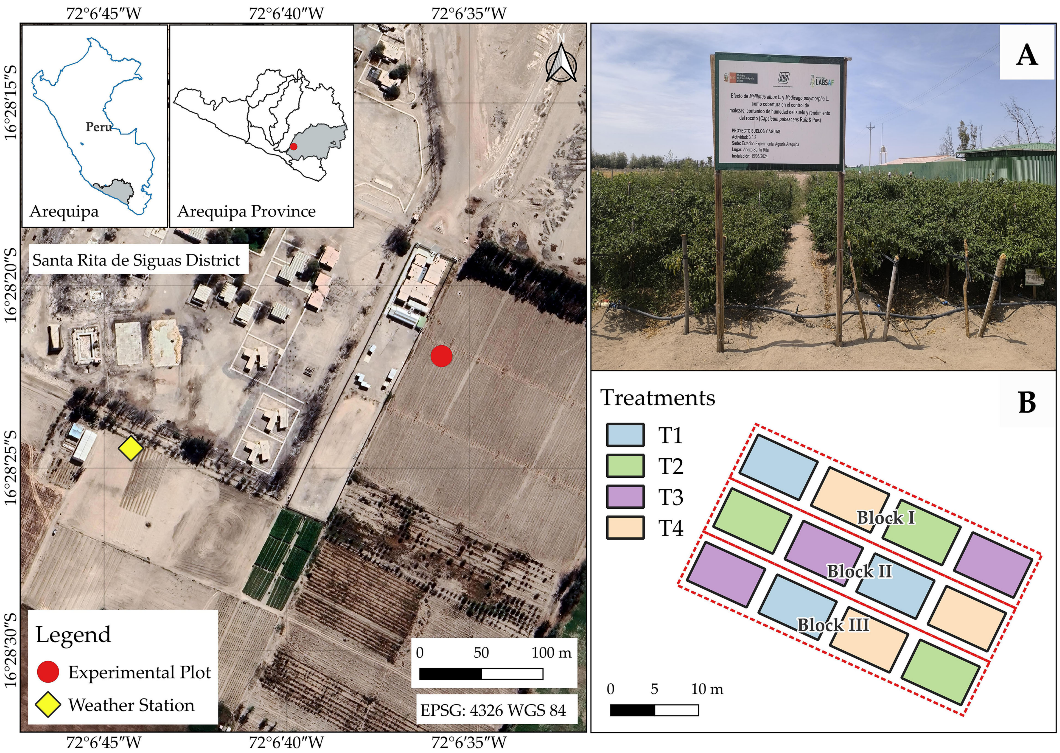

FIGURE 1
Study area. Location of the experimental plot and weather station at the Arequipa Agrarian Experimental Station – INIA, Santa Rita de Siguas district, Arequipa province, Arequipa region, Peru. **(A)** Image of the surrounding area of the experimental plot of the rocoto (*Capsicum pubescens* Ruiz & Pav.) plot during the fruiting stage. **(B)** Layout of the experimental plot.

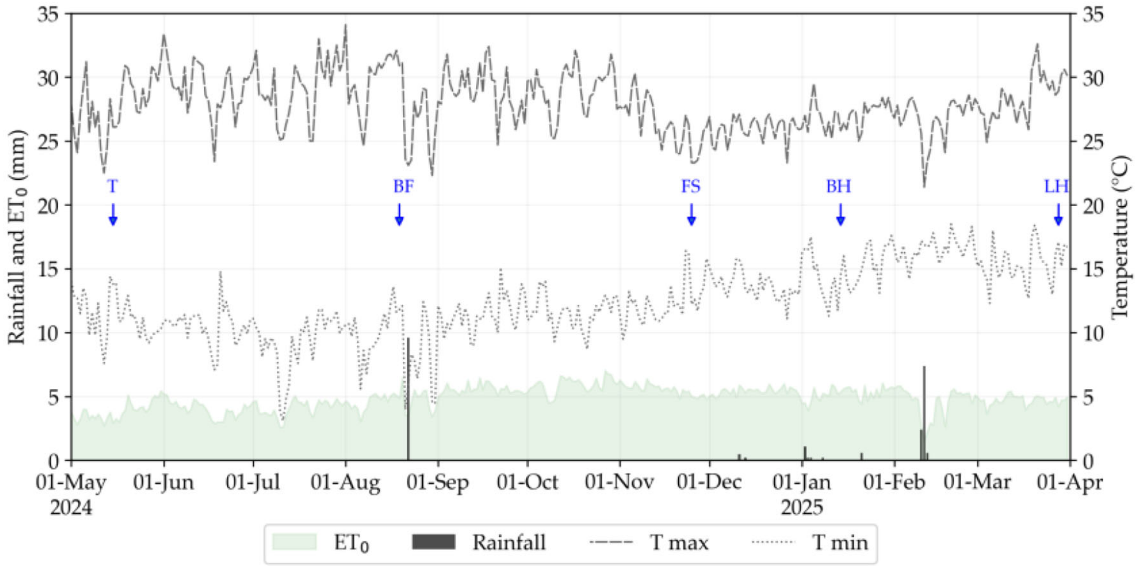

FIGURE 2
Meteorological parameters during the 2024–2025 growing season. Potential evapotranspiration (ET_0), precipitation, maximum temperature (Tmax), and minimum temperature (Tmin) during crop development. Blue arrows indicate the beginning of each phenological stage: transplanting (T); beginning of flowering (BF); fruiting stage (FS); beginning of harvest (BH); and last harvest (LH).

measuring 1.2 × 0.8 m, provided a planting density of 10,416 plants·ha^{-1}. The treatments were as follows: T1 – soil cover with *Melilotus albus*; T2 – soil cover with *Trifolium pratense*; T3 – plastic mulch; and T4 – manual weeding (control). A RCBD was employed to control for potential longitudinal edaphic variability across the experimental field.

2.3 Physicochemical characteristics of the soils

Prior to the establishment of the experimental plot, a composite soil sample was collected from the topsoil layer (0–30 cm) and analyzed at the Soil, Water, and Foliar Analysis Laboratory (LABSAF) of INIA Arequipa to determine its physicochemical properties. The soil was characterized as loamy sand, comprising 80.9% sand, 11.3% silt, and 7.9% clay, as determined by the Bouyoucos hydrometer method (Bouyoucos, 1962). The pH was 7.4 (ISO, 1982), and electrical conductivity (EC 1:5) was 1.05 dS·m^{-1} (Standardization, 1994). Organic matter content was 1.30% (Walkley and Black, 1934), available phosphorus (P) was 30.40 mg·kg^{-1} (Olsen and Sommers, 1982), and available potassium (K) was 598.80 mg·kg^{-1} (DOF - Diario Oficial de la Federación).

2.4 Experimental plot management

The experiment was conducted between May 2024 and March 2025. The land was prepared by subsoiling, ploughing, and leveling using a John Deere 6110D tractor, forming raised beds 0.30 m in heigh and spaced 1.20 m from center to center, resulting in an effective bed width of 0.80 m. A drip irrigation system was installed, consisting of a 2″ main line, 1″ distribution lines, and 16 mm lateral lines with 1.5 L·h^{-1} emitters at 60 kPa every 0.20 m, along with a fertigation arc equipped with ¾″ Wade Rain Venturi injectors.

Prior to transplanting, the beds were irrigated for one hour. Forty-day-old rocoto seedlings with 4–6 true leaves of the accession ‘rocoto rojo de la selva central’, obtained from a local nursery, were used. Plants were transplanted in a single row at the center of each bed, maintaining a spacing of 0.80 m between plants, which extrapolated to a density of 10,416 plants·ha^{-1}.

Based on the soil characteristics, a fertigation dose of 200–100–200 kg·ha^{-1} of N (as ammonium nitrate), P_2O_5 (as monoammonium phosphate), and K_2O (as potassium nitrate) was applied at seven-day intervals, starting two days after transplanting (DAT). The fertilization was split according to the requirements of each phenological stage: vegetative growth (40%-60%-15% of N-P_2O_5-K_2O), flowering (25%-20%-30%), fruiting (20%-15%-30%), and maturation (15%-5%-25%).

At 120 DAT, staking was performed by placing two 1.2-meter-high posts at the ends of each bed, connected with ropes. Additionally, an individual 1.2-meter stake was installed for each plant. These practices aimed to ensure plant stability and minimize the risk of fruit-soil contact.

Pest and disease control of the crop was carried out based on field evaluations. For the management of *Thrips* spp., *Bemisia tabaci*, and *Myzus persicae*, LOVERA® (lambda-cyhalothrin + thiamethoxam; 20 mL per 20 L backpack sprayer; applied at 26, 64, 105, 148, 188, 225 and 243 DAT) and KRAKEN® (imidacloprid + lambda-cyhalothrin; 20 g per 20 L; applied at 47, 84, 125, 170, 214 and 238 DAT) were sprayed alternately. CIPERMEX® Super 10 CE (alpha-cypermethrin; 30 mL per 20 L; applied at 63 and 98 DAT) was used for larval control. To manage *Tetranychus urticae*, DK-TINA® (abamectin; 15 mL per 20 L) was applied to both the main crop and *Trifolium pratense* living cover at 148, 217, 231, and 243 DAT. Control of *Leveillula taurica* on living covers and *Botrytis cinerea* on rocoto was achieved with PROTEXIN® 500 FW (carbendazim; 30 mL per 20 L; applied at 98, 112, and 180 DAT) and EPICO® 750 WG (tebuconazole + azoxystrobin; 20 g per 20 L; applied at 148 DAT). For the control of *Phytophthora capsici*, PREDOSTAR® (propamocarb + metalaxyl; 30 g per 20 L; applied at 125 and 180 DAT) and ALIETTE® WG (fosetyl-Al; 2.5 kg ha^{-1}; applied at 169, 186, and 208 DAT) were used. All products were applied via foliar spray, except for fosetyl-Al, which was applied through the irrigation system.

Harvesting was staggered using hand scissors to prevent damage and maintain fruit quality. Fruits were harvested with their peduncles attached to extend post-harvest shelf life, depending on their stage of maturity. The final harvest took place at 316 DAT, marking the end of the experiment.

2.5 Water requirement

The irrigation program was initially designed based on historical data from the Majes Meteorological Station. Subsequently, specific adjustments were made for each treatment using a soil moisture meter (FIELDSCOUT TDR 150, Spectrum Technologies, Inc., Aurora, Illinois, USA). The adjustments aimed to maintain a soil moisture content of around 9%, as Ratliff et al. (1983) reported that the typical moisture thresholds for loamy sand soil are 16% at field capacity and 7% at the permanent wilting point, representing 9% available water.

The water requirement was determined using the irrigation depth (ID), based on the formula proposed by Allen et al. (1998) , as shown in Equations 1, 2:

$$ID = ET_c - P_e \tag{1}$$

$$ET_c = ET_0 \times K_c \tag{2}$$

Where *ID* is the irrigation depht (mm), ET_c is the crop evapotranspiration (mm), P_e is the effective precipitation (mm), ET_0 is the reference evapotranspiration (mm), and K_c is the crop coefficient. P_e was estimated using the method proposed by the USDA (Smith, 1992). The ET_0 value was calculated using the Penman-Monteith equation modified by the FAO (Allen et al., 1998), based on climate data recorded at the Santa Rita weather station. The K_c coefficient varied according to the crop's phenological stage, with the following values: 0.65 during vegetative growth, 0.97 at flowering, 1.06 during fruiting, and 1.13 at maturity (Sánchez Vesga et al., 2003).

2.6 Establishment of coverage

The selected species were *Trifolium pratense* var. americano, whose seeds were obtained from the local market, and *Melilotus albus*, whose seeds were collected from the field due to its behavior as a weed. Although the introduction pathway of *M. albus* into Peru is unknown, it has successfully adapted to desert regions such as Arequipa (Quipuscoa Silvestre et al., 2016) and is currently naturalized in various agricultural systems. Propagation was conducted in 288-cell trays using PROMIX-GTX (a blend of blond peat and vermiculite) as the substrate. Seven seeds were sown per cell. At 125 DAT of the rocoto crop, *M. albus* and *T. pratense* seedlings, 35 days old, were transplanted according to their respective T1 and T2 treatment layouts. The seedlings were arranged in four rows (two on each side of the main crop) with 10 cm spacing between plants, following manual weeding to ensure uniform experimental conditions. Treatment T3 involved a synthetic cover consisting of white-on-black plastic mulch (50-micron polyethylene with >60% visible light reflectance), which was installed at 28 DAT. Treatment T4 consisted of a no-cover control, where manual weeding was performed on 44, 61, 98, 125, and 155 DAT.

2.7 Biometric and physiological parameters

Plant height was measured every 7 days, starting at 5 DAT, in six representative plants per experimental unit, recording the distance from the stem base (collar) to the apex of the plant stem. The chlorophyll index was assessed in fully developed young leaves following the methodology described by Hu et al. (2010). Three plants per experimental unit were evaluated, considering three readings taken per plant. Measurements were conducted using a SPAD-502 Plus chlorophyll meter (Soil Plant Analysis Development), which provides an index proportional to the chlorophyll content in the leaf. Evaluations of the plants' phenological behavior included monitoring the onset of flowering. An experimental unit was considered to have reached this stage when more than 50% of the plants exhibited visible signs of flowering (Arcila Pulgarín, 2007).

After harvesting, the fruits were selected and classified by size and weight according to the criteria described by Sardón Mamani (2015) *Bola*, with a height of 5.1 cm, width of 5.6 cm, and weight less than 100 g; *Primera*, with a height of 6.2 cm, width of 6.8 cm, and weight between 100 and 140 g; *Extra*, with a height of 6.9 cm, width of 8.5 cm, and weight between 140 and 160 g; and *Super Extra*, with a height of 8.7 cm, width of 9.6 cm, and weight greater than 189 g. Classification was performed on six representative plants per experimental unit, from which yield data were obtained. Yields were extrapolated to tons per hectare ($t{\cdot}ha^1$) and number of fruits per treatment. The dry matter content was determined using a 5 g fruit sample, which was cut into cubes, homogenized, and weighed with an electronic balance (Explorer™ Pro Precision, Ohaus, USA; accuracy: 0.001 g). The sample was dried in an oven (Memmert Schwabach 854) at 105°C until a constant weight was achieved, following the AOAC 930.15 method (Brilhante et al., 2024).

 10.3389/fagro.2025.1663633

Soil volumetric moisture was monitored using a FIELDSCOUT TDR 150 (Time Domain Reflectometer), with six measurements taken per experimental unit every 7 days starting at 33 DAT, at a depth of 20 cm. This depth was selected based on Grasso et al (Grasso et al., 2020), who reported that under drip irrigation, approximately 80% of the root system of *Capsicum annuum* is concentrated within the top 20 cm of soil. Additionally, it has been established that the easily evaporable layer in sandy loam soils is approximately 5 cm deep (Lehmann and Or, 2024) and that the wetting bulb depth in drip irrigation systems reaches around 20 cm in soils with similar characteristics under comparable irrigation durations (Hao et al., 2007).

2.8 Determination of weed control and living cover biomass

Weed control by living covers was assessed by counting the number of individuals per square meter (weed density), as described by Braun-Blanquet (1932). Three representative evaluations were conducted at 173, 202, and 254 DAT. Weed species were classified into functional groups based on their morphological characteristics: broadleaf weeds (dicotyledons) and narrow-leaf weeds (grasses), according to Najul and Anzalone (2006).

To evaluate the biomass of the living covers (*Melilotus* and *Trifolium*), three samples were collected per experimental unit following the method described by Baldivieso et al (Baldivieso-Freitas et al., 2018). Each sample covered an area of 1 m^2 and was taken from the head, middle, and tail sections of different beds. The aerial parts of the plants were cut and weighed to determine fresh weight, while the roots were extracted and washed before being weighed. Both the aerial and root parts were dried in an oven at 60 ° C for 48 hours to obtain their dry weights. Dry biomass was then calculated based on these measurements.

2.9 Determination of N, P, and K in the biomass of living covers

To determine the total nitrogen (N), phosphorus (P), and potassium (K) content in the aerial and root biomass of the living covers, representative subsamples were collected, oven-dried at 65°C to a constant weight, ground, and sent to the laboratory (150 g per experimental unit). Total nitrogen was quantified using the Kjeldahl method, following the ISO 11261:1995 (International Organization for Standardization, 1995). Total phosphorus was determined using the AS-11 method, based on the Bray and Kurtz procedure (Bray and Kurtz, 1945), as specified in the Mexican Official Standard NOM-021-RECNAT-2000 (DOF - Diario Oficial de la Federación). Total potassium was analyzed using the modified AS-12.2002 method, as described by Semarnat et al (DOF - Diario Oficial de la Federación). All analyses were conducted at the Soil, Water and Foliar Analysis Laboratory (LABSAF) of INIA Arequipa.

2.10 Statistical analysis

Variables assessed at the end of the growing season (i.e., fresh and dry yields, and dry biomass and nutritional composition of living mulches) were evaluated using analysis of variance (ANOVA). Significant differences were analyzed using Tukey's test (α = 0.05). Assumptions of normality and homoscedasticity were verified using Shapiro-Wilk and Bartlett's tests, respectively.

Variables measured repeatedly over time (i.e., plant height, chlorophyll index, soil volumetric moisture content, and weed density) were analyzed using generalized linear mixed models (GLMM), also evaluating the random effect of plots. The corrected Akaike information criterion (AICc) was applied for model selection. Thus, Tweedie distribution with square root link was used for plant height and SPAD variables; beta distribution with logit link for soil moisture; and Tweedie distribution with logarithmic link for weed density. The significance of fixed effects and their interactions was evaluated using likelihood ratio tests (Chi^2), and statistically significant factors and combinations ($p < 0.05$) were reported.

Discrete variables (i.e., flowering onset and number of fruits per plant) were analyzed using the Kruskal-Wallis test, applying Dunn's test as *post hoc* analysis (α = 0.05) in case of significant differences. InfoStat version 2020 (Di Rienzo et al., 2020) was used for ANOVA analyses, and R version 4.4.3 (R: The R Project for Statistical Computing) for the other aforementioned analyses.

3 Results

3.1 Development of living covers

Trifolium pratense germinated 3 days after sowing (DAS), while *Melilotus albus* emerged at 7 DAS. During the seedling stage, *T. pratense* exhibited greater uniformity and vigor, with an average of 6 viable seedlings per cell, compared to only two seedlings in *M. albus*, which was affected by intraspecific competition. At the time of transplanting (at 35 DAS), *T. pratense* reached a height of 12 cm and displayed dense foliage, whereas *M. albus* measured 8 cm and exhibited limited foliar development. In field conditions, however, *M. albus* demonstrated accelerated growth, attaining a height of 135 cm at 132 days, in contrast to 30 cm for *T. pratense*. In terms of root development, *T. pratense* formed a dense fasciculated and shallow root system, while *M. albus* developed a thick taproot with lower lateral root density.

3.2 Biometric and physiological variables

The GLMM used for plant height explained 98% of the observed variation in the data (Supplementary Table S1). Thus, plant height (Supplementary Figure S1) varied significantly as a function of time (i.e., days after transplanting), but not according to the applied treatments. Regarding the chlorophyll index, the best-fitting model explained no more than 37% of the observed deviance in the data (Supplementary Table S2). Overlapping confidence bands were identified for the five evaluation timepoints across the four treatments (Supplementary Table S3). They highlight the non-significant differences in the evaluations conducted after the implementation of the cover crops.

3.3. Yield variables

No significant differences were observed in fruit number per plant, fruit dry matter (Supplementary Table S4), or total yield (Table 1). However, T3 and T4 exhibited a tendency toward higher values with reduced variability. The analysis by commercial categories revealed significant differences for Primera Category (C3), where T4 achieved the highest values. No treatment produced fruits classified as Extra Super Category (C1).

3.4 Soil volumetric moisture

The GLMM with beta distribution and logit link explained 95% of the variation in soil volumetric moisture (SVM) (Supplementary Table S5). A significant effect was observed in the quadratic interaction between treatments and time, revealing differentiated trajectories. T1 and T4 maintained stable moisture levels (≈12–15%) throughout the entire period, while T2 and T3 exhibited contrasting patterns. T2 started with the lowest SVM (≈11.1%) and increased progressively toward day 245, whereas T3 initiated with the highest moisture content (≈28.9%) and decreased quadratically after the plastic mulch was installed and the irrigation time proportion was reduced by approximately 50% (Figure 3B). The establishment of living coverage in T1 and T2 increased their irrigation time proportion (Figure 3A). After 166 DAT, the volume of water applied to T1 and T2 was increased. T2 significantly showed greater soil moisture content than T1 despite both receiving the same irrigation volumes. The maximum effect was recorded at 257 DAT (maturation of *M. albus*) coinciding with the peak development of the aerial and root biomass of the living cover. From 266 DAT onward, all treatments converge toward similar irrigation time proportions, coinciding with the crop's maturation stage.

Analysis of variance revealed significant differences among treatments for irrigation water productivity (IWPt) ($F = 8.53$; $p = 0.0139$). Treatment T3 demonstrated the highest water use efficiency, with IWPt values significantly superior (2.2 and 2.0 times) compared to T1 and T2, respectively (Table 2). Treatment T4 exhibited intermediate behavior, with no significant differences from T3 or the T1-T2 group. These results reflect a significant effect of applied irrigation volume on IWPt, where the volume reduction in T3 (6690 m^3 ha^{-1}) resulted in statistically higher efficiency compared to treatments with greater water input (T1 and T2: 9635 m^3 ha^{-1}).

3.5 Potential contribution of biomass and nutrients to the soil

T1 produced significantly greater above-ground dry biomass (8.57 t·ha^{-1}) compared to T2 (3.04t·ha^{-1}), whereas T2 exhibited higher root biomass (1.42 vs. 0.56 t·h^{-1}) as shown in Figure 4. The total N, P, and K content potentially contributed to the soil by living covers did not differ significantly between treatments (Table 3). However, organ-specific analysis revealed distinct patterns: *Trifolium pratense* (T2) showed higher concentrations of P and K in the roots, while *Melilotus albus* (T1) was notable for its elevated K content in the above-ground biomass.

3.6 Control of broadleaf weeds and grasses

The GLMM model (Tweedie distribution, log link; AICc = 216.16) explained 99% of the variation in weed density. The Treatment × Type interaction ($\chi^2 = 9.69$; $p < 0.01$) was significant (Supplementary Table S6), as was the main effect of time. Weed presence decreased progressively over time (Figure 5A); T1 and T2 showed similar efficacy in controlling broadleaf weeds, whereas T2 demonstrated superior efficiency in controlling grass-type weeds (Figure 5B).

TABLE 1 Rocoto yield by commercial categories.

Treatments	C2 (t·ha^{-1})	C3 (t·ha^{-1})	C4(t·ha^{-1})	Y (t·ha^{-1})
T1	0 ± 00	3.77 ± 0.87 ^{b}	35.78 ± 3.26	39.55 ± 2.39
T2	1.98 ± 1.06	4.05 ± 1.43 ^{b}	37.91 ± 9.30	43.94 ± 9.24
T3	0.52 ± 0.52	4.38 ± 1.51 ^{b}	56.42 ± 2.63	61.32 ± 3.95
T4	1.57 ± 1.57	13.35 ± 3.37 ^{a}	46.55 ± 2.51	61.47 ± 6.90
F-value	1.24	8.42	2.15	2.18
p-value	0.371	0.015	0.201	0.196
Significance	NS	*	NS	NS

C1: Super Extra category (not included since no fruits were produced in any treatment); C2: Extra category; C3: Primera category; C4: Bola category; Y: total yield. Data were extrapolated to t ha^{-1} and are expressed as mean ± standard error. Different letters within each variable indicate statistically significant differences among treatments at $p < 0.05$ according to Tukey's test. NS, not significant; * = significant at $p < 0.05$.

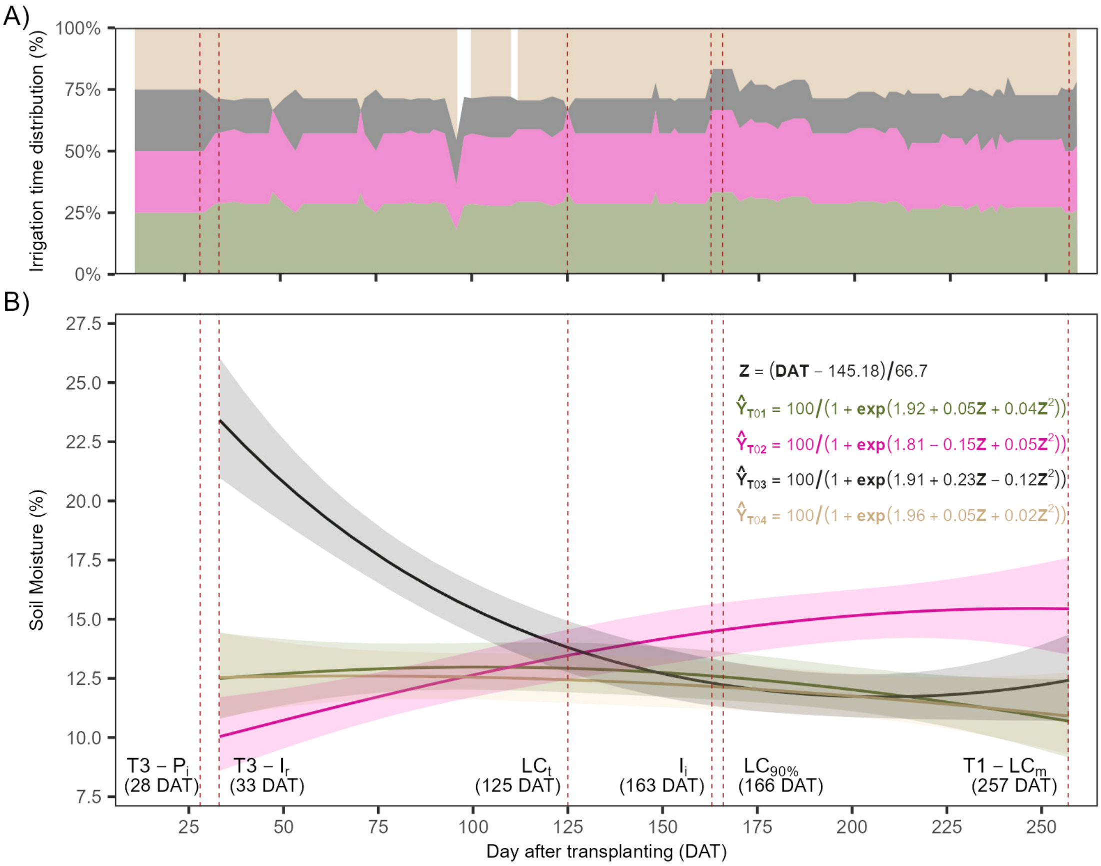

FIGURE 3
Irrigation time distribution (%) and soil moisture (%). **(A)** Proportional distribution of irrigation time among treatments throughout the crop cycle. **(B)** Evolution of soil moisture by treatment during the cropping period. Arrows indicate key events: 28 DAT – Plastic installation (Pi) in T3; 33 DAT – Irrigation reduction (Ir) in T3; 125 DAT – Living cover transplanting (LCt) in T1 and T2; 163 DAT – Irrigation increment **(Ii)** in T1 and T2; 166 DAT – Living cover at 90% (LC90%) in T1 and T2; 257 DAT – Living cover maturity (LCm) in T1.

4 Discussion

4.1 Uniform behavior among treatments

The cover treatments (T1: *Melilotus albus*, T2: *Trifolium pratense*, T3: plastic mulch, T4: no cover) did not result in significant differences in plant height, Chlorophyll index, flowering onset, fruit number, or dry matter content of rocoto fruits. This lack of variation could be attributed to factors related to nitrogen nutrition and the timing of evaluation. Aminifard et al. (2012) demonstrated that variations in nitrogen fertilization significantly influence these parameters in peppers; however, in the present study, all treatments received the same mineral fertilization regime. As noted by Havlin et al. (2016), symbiotically fixed nitrogen is primarily utilized by the host legume, with minimal release into the soil during its life cycle. It becomes available to the main crop only after the legume biomass is decomposed and incorporated into the soil.

Chu et al. (2017) emphasize that the evaluation period is a determining factor, as the benefits of living covers tend to manifest predominantly in the medium- to long-term. Similarly, plastic mulch did not exhibit immediate effects. Hochmuth and Hochmuth (1994) reported that white-on-black plastic mulch did not influence the number of pepper fruits during the first year of evaluation. However, positive effects emerged in the second year.

TABLE 2 Irrigation Water Productivity (kg m^{-3}) related to the total rocoto yield.

Treatment	Irrigation volume (m^3 ha^{-1})	IWPt (kg m^{-3})
T1	9635	4.11 ± 0.43^{b}
T2	9635	4.56 ± 1.66^{b}
T3	6690	9.17 ± 1.02^{a}
T4	9195	6.68 ± 1.3^{ab}
p-value		0.0139
F-value		8.525

4.2 Response of fruit yield to cover management

In this study, no statistically significant differences were detected in total yield (Y) or in the Extra (C2) and Bola (C4) fruit

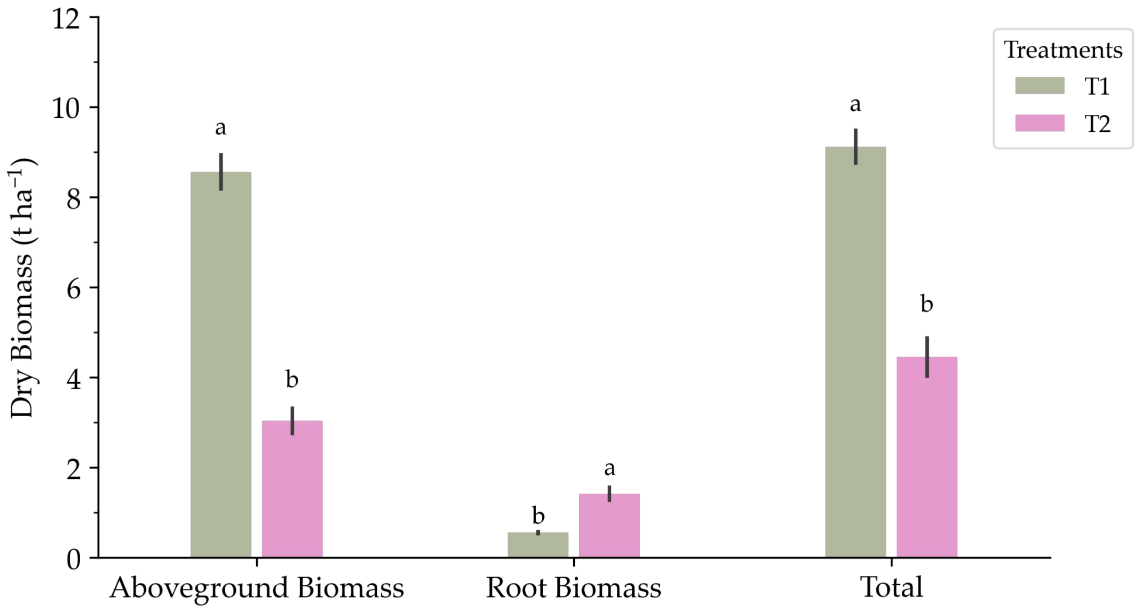

FIGURE 4
Organ-specific dry biomass of *Melilotus albus* (T1) and *Trifolium pratense* (T2), separated into aboveground biomass, root biomass, and total biomass. Data are presented as mean ± standard error. Different letters above the bars indicate statistically significant differences between treatments for each evaluated component (Tukey test, $p < 0.05$).

categories among treatments. Although certain trends were observed in mean values, these should be interpreted with caution due to the high variability recorded, particularly in treatment T2. This level of dispersion reduced the statistical power of the analysis and limited the detection of effects attributable to cover management, a situation also reported by other authors in experiments with high genetic or environmental heterogeneity (Gómez and Gomez, 1984).

These results are consistent with studies in *Capsicum* and other crops showing that traits related to yield and quality are highly sensitive to environmental factors such as radiation, humidity, and nutrient availability (Zewdie and Bosland, 2000; Sahmat et al., 2024). Consequently, genotype stability cannot be evaluated solely on the basis of mean yield, but requires considering its differential response under contrasting environmental conditions (Sran et al., 2021; Sahmat et al., 2024). A key aspect to consider is the marked

TABLE 3 Contribution of N, P, and K from living cover biomass.

Organ biomass	Treatments	N (kg·ha^{-1})	P (kg·ha^{-1})	K (kg·ha^{-1})
Roots	T1	4.55 ± 2.04 ^{a}	1.74 ± 0.03 ^{b}	2.95 ± 0.05 ^{b}
	T2	14.91 ± 5.38 ^{a}	5.70± 0.87 ^{a}	17.67 ± 1.07 ^{a}
	F-value	6.21	19.58	180.98
	P-value	0.13	0.047	0.005
Aboveground	T1	73.54 ± 20.26 a	23.31 ± 3.75 a	127.68 ± 6.44 ^{a}
	T2	32.09 ± 26.76 a	10.38 ± 0.69 a	73.90 ± 7.43 ^{b}
	F-value	1.68	8.5	23.09
	P-value	0.32	0.10	0.04
Total	T1	78.09 ± 18.73 a	25.05 ± 3.78 a	130.64 ± 6.41 a
	T2	47.00 ± 22.16 a	16.08 ± 1.18 ^{a}	91.57 ± 6.63 a
	F-value	0.84	3.52	12.92
	p-value	0.45	0.2	0.06

Data are presented as mean ± standard error. Different letters within each organ-nutrient combination represent statistical significance between treatments (Tukey test, $p < 0.05$). F and p values correspond to ANOVA analysis between treatments.

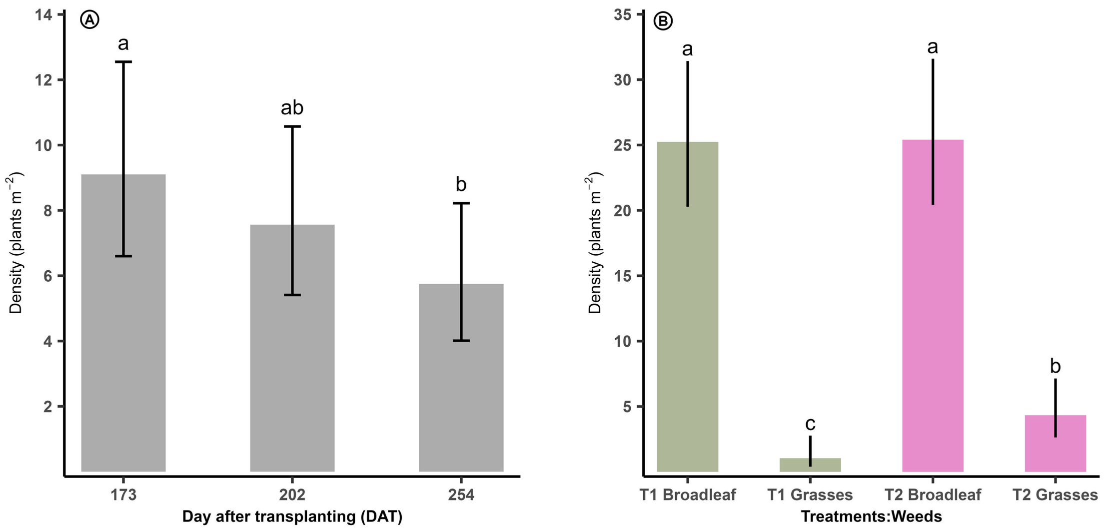

FIGURE 5
Density of broadleaf species and grasses. **(A)** Main effect of DAT. **(B)** Effect of treatment × weed interaction. Error bars represent 95% confidence intervals. Different letters indicate significant differences in density at a significance level of 0.05 according to the False Discovery Rate (FDR) correction method.

climatic discrepancy between the origin of the genetic material and the experimental site. The Oxapampa accession is associated with a production zone characterized by high relative humidity (88%) and low solar radiation (166 W·m^{-2}). In contrast, Santa Rita de Siguas presents opposite conditions, with 49% relative humidity and 279 W·m^{-2} solar radiation, according to SENAMHI data (SENAMHI - Descarga de Datos). This genotype × environment mismatch likely constrained the expression of genetic potential, regardless of treatment. In this regard, climate represents a particularly complex factor, as it integrates relatively predictable components defined by the prevailing climatic regime with unpredictable components derived from interannual variability (Oladosu et al., 2017). Moreover, the relative stability of fruit load, in contrast with the variability of quality traits, highlights the complexity of genotype × environment interactions and their influence on yield stability.

In the Primera (C3) category, significant differences were detected, with treatment T4 (manual weeding) achieving the highest yield. Its superiority over living covers (T1 and T2) may be related to the reduction of interspecific competition, while the difference with plastic mulch (T3) could be associated with accelerated fruit ripening, as previously reported in studies with white mulch (Overbeck et al., 2013). This earlier ripening may have favored the harvest of smaller fruits, thereby reducing the proportion of C3 fruits. However, under conditions of high radiation and low humidity, the influence of both environment and genetic material on this differential response cannot be ruled out. Since this study was conducted during a single growing season, the conclusions should be interpreted within these limitations, as they do not account for interannual variability that could substantially modify the genotype's response.

4.3 Dynamics of volumetric soil moisture

Optimizing water resources is essential in arid regions. In this context, plastic mulch (T3) proved highly effective in conserving water, reducing irrigation time by about 50% and maintaining soil moisture at an optimal content for plant-available water in sandy loam soils (Ratliff et al., 1983). These results align with those of Díaz-Pérez (2010) and Ren et al (Ren et al., 2021), who found higher water content in the top 60 cm of soil when using plastic mulch. Among living cover treatments, T2 shows greater soil moisture retention than T1, indicating improved water use efficiency once fully established. This advantage of *T. pratense* in conserving water is likely linked to differences in its root system. *M. albus* develops deeper, less dense roots near the surface (Ríos et al., 1993), while *T. pratense* has a denser, more superficial root system (Fergus and Hollowell, 1960; Bowley et al., 1984), which favors moisture retention in the upper soil layers. High root density decreases macroporosity (Daly et al., 2015), possibly limiting rapid infiltration but increasing water retention capacity. Additionally, root exudates can alter soil structure and absorb large amounts of water (Xiao et al., 2024), boosting water availability in the rhizosphere. Morphologically, M. albus grows upright and taller, resulting in a larger leaf area exposed to sunlight, which leads to higher transpiration rates. Conversely, the prostrate growth habit and shorter stature of *T. pratense* keep its foliage shaded beneath the rocoto, reducing water loss through transpiration.

The literature confirms that bare soil promotes greater water loss through direct evaporation (Brun et al., 1986; Gomes de Andrade et al., 2011), whereas living covers help reduce both evaporation and runoff, thereby enhancing infiltration and water conservation (Wyngaarden et al., 2015). However, as we found, it depends on the living covers' characteristics. Biazzo and Masiunas (2000) reported that living mulch with *T. pratense* retains more moisture compared to bare soil. Nevertheless, Nielsen and Vigil (2005) and Blanco-Canqui et al. (2015) cautioned that in semi-arid environments, living covers can reduce the moisture available to the main crop by 20–50%, depending on the timing of their suppression and the management practices applied.

To the best of our knowledge, no previous reports of IWPt values are available for *Capsicum pubescens*. In our study, IWPt ranged from 4.11 to 9.17 kg m^{-3}, with higher values observed under plastic cover. However, the variability in the yields obtained, compared with those reported in the literature (Pérez-Grajales et al., 2004; Puente et al., 2014; MIDAGRI, 2025), suggests that further research is needed to better understand water productivity responses in this crop.

4.4 Biomass production by living plant covers and nutrient accumulation

In terms of biomass contribution, T1 (*Melilotus albus*) produced 2.05 times more dry above-ground biomass than T2 (*Trifolium pratense*). This difference is attributed to the erect growth habit and greater height of the *Melilotus* genus, which enables more effective light interception and higher photosynthetic efficiency (Fontana et al., 2018), further supported by its rapid vegetative regrowth from basal shoots (Țîței, 2022).

Conversely, T2 (*Trifolium pratense*) exhibited 2.6 times greater dry root biomass, consistent with its capacity to develop dense and deep root systems (Blanco-Canqui et al., 2015; Dlamini et al., 2024), with reported root dry matter yields ranging from 2.3 to 2.9 t·ha^{-1}.

The above-ground to root biomass ratio differed significantly between species These proportions reflect contrasting ecophysiological strategies. *Melilotus albus* prioritizes above-ground biomass, which is advantageous for forage production or rapid surface coverage, (Țîței, 2022). In contrast, *Trifolium pratense* allocates more biomass to its root system, making it more suitable for biopore formation, enhanced water infiltration and retention, and increased rhizospheric biological activity (Yu et al., 2016; Mckenna et al., 2018; Adetunji et al., 2020).

Living covers can generate significant agronomic interactions with the main crop. In this context, the high above-ground biomass production of *Melilotus albus* may increase competition for light in high-density systems, potentially affecting the development of rocoto pepper. White et al. (2016) note that fast-growing covers with early foliage closure can exert intense physical competition and may also release allelopathic compounds. In contrast, species such as *Trifolium pratense*, which produce less above-ground biomass, may reduce such competition in polyculture systems (Thorsted et al., 2006). Their greater biomass allocation to the root system, however, contributes to improved soil physical structure and the formation of stable aggregates (Mckenna et al., 2018).

As leguminous species, both *Melilotus albus* and *Trifolium pratense* contribute to biological nitrogen fixation; however, the total amount fixed may vary due to differences in biomass production (McEwen and Johnston, 1985; Nesheim and Øyen, 1994; Hernandez Escareño, 1998; Pederson et al., 2002; Terroba et al., 2024).In the present study, although the differences were not statistically significant. This variability among studies can be explained by differences in nitrogen fixation efficiency among legume species, which is influenced by nodule morphology and root system development, with higher efficiency observed in species with more developed root systems (Terpolilli et al., 2012).

The total nutrient accumulation (from root and above-ground biomass) indicates that *Melilotus albus* (T1) can contribute 78.09 kg N·ha^{-1}, 25.05 kg P·ha^{-1}, and 130.64 kg K·ha^{-1}. In comparison, *Trifolium pratense* (T2) contributes 47.00 kg N·ha^{-1}, 16.08 kg P·ha^{-1}, and 91.97 kg K·ha^{-1}. However, this contribution will only effectively improve soil fertility after biomass incorporation, and the availability of nutrients for the subsequent crop will depend on the decomposition rate, moisture and temperature conditions, the residue's C/N ratio, and soil microbial activity (Havlin et al., 2016; Weil and Brady, 2017).

4.5 Broadleaf and grass weed control

Although treatments T3 (plastic mulch) and T4 (manual weeding) are not shown in Figure 5, both achieved complete weed control. The synthetic cover and manual weeding eliminated weed competition, aligning with findings by Kasirajan and Ngouajio (Sokombela et al., 2025), who reported that plastic mulches block photosynthetically active radiation, which is necessary for weed germination. Similarly, studies by Barla et al. (2018) and Mzabri et al. (2021) confirm that plastic mulching effectively reduces weed biomass, yielding results comparable to those achieved with chemical treatments and superior to those obtained with organic mulching.

Treatments with living covers (T1 and T2) showed no statistically significant differences in terms of broadleaf weeds; however, T2 was more effective at controlling grasses weeds, suggesting a selective suppressive effect. Living covers suppress weeds through multiple mechanisms: allelopathy (Fujii, 2003), competition for resources (Williams et al., 1998), reduced light availability (Teasdale and Mohler, 2000), and the release of allelochemical compounds that enhance shading and competition (Mohammadi and Mohammadi, 2012).

The temporal weed control T2 suggests that this cover may favour the growth of particular grass species. According to Brainard et al (Brainard et al., 2011), leguminous covers may be less effective at weed suppression due to unpredictable fluctuations in temperature and soil fertility, reducing their suppressing effectiveness.

The results have practical implications for integrated weed management. While synthetic mulches and manual weeding offer higher effectiveness, they require greater financial investment or labour inputs (Steinmetz et al., 2016). In contrast, plant covers, although less effective at suppressing weeds, provide additional benefits, including moisture conservation, contribution of organic matter, and enhanced biodiversity (Teasdale, 1996; Blanco-Canqui et al., 2015). However, the prolonged use of plastic mulch can alter soil biocoenosis, increase greenhouse gas emissions, and lead to the accumulation of plastic residues in the soil (Steinmetz et al., 2016). Although biodegradable alternatives are available, their high cost limits their widespread adoption compared to polyethylene mulch (Sokombela et al., 2025), underscoring the need for a comprehensive assessment of their use. This challenge is exemplified in China, where the accumulation of 550,800 tons of plastic residues resulted in a 6–10% reduction in cotton yields (Zhang et al., 2020). The problem is further exacerbated by the projected growth of the global synthetic mulching market, estimated to reach USD 19.49 billion by 2029 with an annual growth rate of 7.1% (MarketsandMarkets, 2025), while the high recovery costs undermine its long-term economic feasibility (Steinmetz et al., 2016). On the other hand, manual weeding, although effective for weed removal, has limitations that reduce its feasibility in large areas due to its high demand for labor, physical effort, and time, which substantially increase operational costs (Hujerová et al., 2016; Assani Bin Lukangila et al., 2024). Moreover, its environmental benefits are limited compared to those provided by living covers (Poeplau and Don, 2015; Koudahe et al., 2022).

4.6 Management recommendations for cover crops in arid zones

4.6.1 Scenarios of severe water scarcity

In the context of the arid regions of Arequipa, where water availability is limited, plastic mulch showed potential as a strategy to conserve soil moisture and reduce weed incidence, which could contribute to improving water use efficiency (WUE).

As a sustainable alternative, it is recommended that the economic viability of biodegradable plastics be assessed. Despite their higher initial cost, their implementation should be evaluated through a cost-benefit analysis that considers reduced labor requirements for post-harvest removal, decreased environmental impact, and the potential for enhanced marketability of products under sustainable certifications.

4.6.2 Strategies for organic matter enrichment

Arid soils, such as those found in Arequipa, with low organic matter content (1.31% in this study), tend to present limitations in water retention, cation exchange capacity, and biological activity. In this context, high-biomass leguminous cover crops, particularly *Melilotus albus* due to its drought tolerance, nitrogen-fixing capacity, and high above-ground biomass production, may represent a promising alternative. The biomass could potentially be used as green manure or compost input, contributing to a circular economy approach within systems that also employ plastic mulch.

4.6.3 Management under moderate water availability conditions

In arid zones where water availability is sufficient, the establishment of *Trifolium pratense* may offer potential benefits, as it can provide multiple ecosystem services such as improved soil moisture retention, increased organic matter content, and atmospheric nitrogen fixation.

Furthermore, in compacted soils, its dense and fasciculated root system may contribute to biological decompaction, enhancing water infiltration and improving soil structure. This hypothesis requires experimental validation through medium- and long-term monitoring of soil physical parameters.

4.7 Study limitations and recommendations for future research

The main limitations of this study include its confinement to a single agricultural season, which restricts the assessment of interannual variability and the cumulative effects of living covers over the medium and long term. The limited number of replicates reduces the statistical robustness of the findings and hampers the detection of significant differences among treatments. Furthermore, variations in irrigation timing, implemented as part of the management strategy, prevented valid statistical comparisons of soil moisture retention across all treatments, thereby limiting the objective quantification of this key parameter. Finally, measuring moisture only at 20 cm depth may not fully capture the dynamics in deeper soil layers.

For future research, it is recommended to integrate management variables, soil moisture measurement at different depths, differentiated irrigation levels, crop associations, and various cover crop species (including grasses, cruciferous plants, and legumes) according to the local agroecological conditions, and family farming systems.

5 Conclusions

The use of soil covers in rocoto pepper (*Capsicum pubescens*) cultivation under arid conditions was insufficient to produce significant effects on most production variables evaluated during the growing season studied. However, plastic mulching showed potential for water use efficiency and weed control under the established experimental conditions. Among the living mulches evaluated, *Trifolium pratense* tended to register greater soil moisture retention than *Melilotus albus*, with differences of up to 63.3% observed during the maturation stage of *Melilotus albus*. In terms of biomass contribution to the soil, *Melilotus albus* evidenced favorable characteristics as a living mulch contributor. This behavior could be associated with its morphological characteristic and observed growth patterns. Regarding nitrogen input through biomass incorporation, both leguminous species demonstrated nitrogen accumulation potential, with *Melilotus albus* exhibiting numerically higher values that did not achieve statistical significance (P > 0.05). For weed control, both living mulches provided moderate weed suppression without significant differences between species, though showing reduced efficacy compared to plastic mulching or manual weeding. The patterns observed in this study require multi-year evaluation to establish their consistency and validity. Consequently, future research should incorporate medium to long-term experimental designs, increase replication numbers, and broaden the scope of assessed variables to derive more robust conclusions regarding soil cover utilization in rocoto pepper production under arid conditions.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

RP: Formal Analysis, Investigation, Methodology, Writing – original draft. EC: Conceptualization, Formal Analysis, Investigation, Methodology, Writing – original draft. RF: Conceptualization, Writing – review & editing. AQ: Methodology, Writing – original draft. RS: Supervision, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This research was funded by the INIA project CUI 2487112 "Mejoramiento de los servicios de investigación y transferencia tecnológica en el manejo y recuperación de suelos agrícolas degradados y aguas para riego en la pequeña y mediana agricultura en los departamentos de Lima, Áncash, San Martín, Cajamarca, Lambayeque, Junín, Ayacucho, Arequipa, Puno y Ucayali".

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fagro.2025.1663633/full#supplementary-material

References

Adetunji, A. T., Ncube, B., Mulidzi, R., and Lewu, F. B. (2020). Management impact and benefit of cover crops on soil quality: *A review. Soil Tillage Res.* 204, 104717. doi: 10.1016/j.still.2020.104717

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M (1998). *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements.* (FAO Irrigation and Drainage Paper No. 56). (Rome, Italy: Food and Agriculture Organization of the United Nations).

Alyokhin, A., Nault, B., and Brown, B. (2019). Soil conservation practices for insect pest management in highly disturbed agroecosystems – a review. *Entomol. Exp. Appl.* 168, 7–27. doi: 10.1111/eea.12863

Aminifard, M. H., Aroiee, H., Nemati, H., Azizi, M., and Khayyat, M. (2012). Effect of nitrogen fertilizer on vegetative and reproductive growth of pepper plants under field conditions. *J. Plant Nutr.* 35, 235–242. doi: 10.1080/01904167.2012.636126

Anglade, J., Billen, G., and Garnier, J. (2015). Relationships for estimating N2 fixation in legumes: incidence for N balance of legume-based cropping systems in Europe. *Ecosphere* 6, 1–24. doi: 10.1890/ES14-00353.1

Arcila Pulgarín, J.. (2007). Crecimiento y desarrollo de la planta de café. En J. Arcila-Pulgarín, F. F. Farfán V., A. M. Moreno B., L. F. Salazar G., & E. Hincapié G. (Eds.), Sistemas de producción de café en Colombia (pp. 21–60)

Assani Bin Lukangila, M., Kirika Ansey, B., Bugeme Mugisho, D., Kanyenga Lubobo, A., and Kalonji Mbuyi Wa Mbombo, A. (2024). Evaluating the effect of manual hoeing and chemical weed management practices on the productivity and profitability of dry bean (*Phaseolus vulgaris* L.) in the south-eastern zone of the DR Congo. *Phytoparasitica* 52 (4), 55. doi: 10.1007/s12600-024-01172-4

SENAMHI - Descarga de Datos. Available online at: https://www.senamhi.gob.pe/site/descarga-datos/ (Accessed June 26, 2025).

Superficie Agrícola. Available online at: https://siea.midagri.gob.pe/portal/informativos/superficie-agricola-peruana (Accessed June 26, 2025).

Mulching (Ac.) (484) Conservation Practice Standard | Natural Resources Conservation Service. Available online at: https://www.nrcs.usda.gov/resources/guides-and-instructions/mulching-ac-484-conservation-practice-standard (Accessed June 26, 2025).

DOF - Diario Oficial de la Federación. Available online at: https://www.dof.gob.mx/nota_detalle.php?codigo=717582&fecha=31/12/2002gsc.tab=0 (Accessed December 3, 2024).

R: The R Project for Statistical Computing. Available online at: https://www.r-project.org/ (Accessed June 26, 2025).

SENAMHI - Descarga de Datos. Available online at: https://www.senamhi.gob.pe/site/descarga-datos (Accessed June 26, 2025).

Baldivieso-Freitas, P., Blanco-Moreno, J. M., Armengot, L., Chamorro, L., Romanyà, J., and Sans, F. X. (2018). Crop yield, weed infestation and soil fertility responses to contrasted ploughing intensity and manure additions in a Mediterranean organic crop rotation. *Soil Tillage Res.* 180, 10–20. doi: 10.1016/j.still.2018.02.006

Barla, S., Upasani, R.R., Puran, A.N., and Sinha, A. (2018). Effect of plastic mulch and herbicides on weed dynamics and productivity of redgram. *Int. J. Curr. Microbiol. Appl. Sci.* 7, 363–69.

Biazzo, J., and Masiunas, J.B. (2000). The use of living mulches for weed management in hot pepper and okra. *J. Sustain. Agric.* 16, 59–79. doi: 10.1300/J064v16n01_06

Blanco de Alvarado-Ortiz, T. (2016). Su majestad, el rocoto. Universidad Nacional de San Antonio Abad del Cusco, Cusco, Perú.

Blanco-Canqui, H., Shaver, T. M., Lindquist, J. L., Shapiro, C. A., Elmore, R. W., Francis, C. A., et al. (2015). Cover crops and ecosystem services: insights from studies in temperate soils. *Agron. J.* 107, 2449–2474. doi: 10.2134/agronj15.0086

Bouyoucos, G.J. (1962). Hydrometer method improved for making particle size analyses of soils. *Agron. J.* 54, 464–465. doi: 10.2134/agronj1962.00021962005400050028x

Bowley, S. R., Taylor, N. L., and Dougherty, C. T. (1984). Physiology and morphology of red clover. *Adv. Agron.* 37, 317–347.doi: 10.1016/S0065-2113(08)60457-5

Brainard, D. C., Bellinder, R. R., and Kumar, V. (2011). Grass–legume mixtures and soil fertility affect cover crop performance and weed seed production. *Weed Technol.* 25, 473–479. doi: 10.1614/wt-d-10-00134.1

Braun-Blanquet, J. (1932). Plant sociology: The study of plant communities (1st ed.). (New York, NY, & London, England: McGraw-Hill Book Company, Inc).

Bray, R. H., and Kurtz, L. T. (1945). Determination of total, organic, and available forms of phosphorus in soils. *Soil Sci.* 59, 39. doi: 10.1097/00010694-194501000-00006

Brilhante, B. D. G., Santos, T. D. O., Júnior, J. C. C., Rodrigues, V. A. P., Almeida, R. D., Santos, J. O., et al. (2024). Fruit quality and morphoagronomic characterization of a Brazilian capsicum germplasm collection. *Genet. Mol. Res.* 23, gmr19197. doi: 10.4238/gmr19197

Brun, L. J., Enz, J. W., Larsen, J. K., and Fanning, C. (1986). Springtime evaporation from bare and stubble-covered soil. *J. Soil Water Conserv.* 41, 120–122. doi: 10.1080/00224561.1986.12455947

Cai, W., Gu, X., Du, Y., Chang, T., Lu, S., Zheng, X., et al. (2022). Effects of mulching on water saving, yield increase and emission reduction for maize in China. *Agric. Water Manage.* 274, 107954. doi: 10.1016/j.agwat.2022.107954

Chu, M., Jagadamma, S., Walker, F. R., Eash, N. S., Buschermohle, M. J., and Duncan, L. A. (2017). Effect of multispecies cover crop mixture on soil properties and crop yield. *Agric. Environ. Lett.* 2, 170030. doi: 10.2134/AEL2017.09.0030

Daly, K. R., Mooney, S. J., Bennett, M. J., Crout, N. M. J., Roose, T., and Tracy, S. R. (2015). Assessing the influence of the rhizosphere on soil hydraulic properties using X-ray computed tomography and numerical modelling. *J. Exp. Bot.* 66, 2305–2314. doi: 10.1093/jxb/eru509

Díaz-Pérez, C. J. (2010). Bell pepper (Capsicum annuum L.) grown on plastic film mulches: Effects on crop microenvironment, physiological attributes, and fruit yield. *HortScience* 45, 1196–1204. doi: 10.21273/HORTSCI.45.8.1196

Di Rienzo, J. A., Casanoves, F., Balzarini, M. G., Gonzalez, L., Tablada, M., Robledo, C. W., et al. (2020). InfoStat versión 2020. (Córdoba, Argentina: Universidad Nacional de Córdoba).

Dlamini, Z., Jancsó, M., Székely, Á., Kolozsvári, I., Túri, N., Bakti, B., et al. (2024). Assessing yield, biomass production, and forage quality of red clover (Trifolium pratense L.) in agroforestry system: one-year study in Szarvas, Hungary. *Agronomy* 14, 1921. doi: 10.3390/agronomy14091921

Fergus, E. N., and Hollowell, E. A. (1960). Red clover. *Adv. Agron.*, 12, 365–436. doi: 10.1016/S0065-2113(08)60087-5

Fontana, M. C. ,. L., Juan, N. A., Ruiz, M. A., and Babinec, F. J. (2018). Utilización de trébol de olor blanco (Melilotus albus medik.) como abono verde, efecto sobre las condiciones del suelo y la productividad del cultivo subsiguiente use of white sweet clover (melilotus albus medik.) as a green fer tilizer, effect on soil conditions and productivity of subse quent cultivation. *SEMIÁRIDA Rev. la Facultad Agron. UNLPam* 28:25–33. doi: 10.19137/semiarida.2018(02).2533

Fuentes, M., and del, C. (2014). La picantería arequipeña: patrimonio cultural de la nación. Arequipa, Perú. Available online at: https://www.sociedadpicanteradearequipa.pe/images/portada_spa.jpg.

Fujii, Y. (2003). Allelopathy in the natural and agricultural ecosystems and isolation of potent allelochemicals from velvet bean (Mucuna pruriens) and hairy vetch (Vicia villosa). *Biological Sciences in Space* 17, 6–13.doi: 10.2187/bss.17.6

Gomez, K. A., and Gomez, A. A. (1984). Statistical procedures for agricultural research (2nd ed.). New York, NY, USA: John Wiley & Sons.

Gomes de Andrade, J., Seguí, P., Carlesso, R., Trois, C., and Knies, A. E. (2011). Perdidas de agua por evaporación en maíz con siembra convencional y directa para diferentes niveles de cobertura muerta. I. resultados experimentales. *Revista Ciencias Técnicas Agropecuarias*, 20 (2), 60–64.

Grasso, R., de Souza, R., Peña-Fleitas, M. T., Gallardo, M., Thompson, R. B., and Padilla, F. M. (2020). Root and crop responses of sweet pepper (Capsicum annuum) to increasing N fertilization. *Scientia Hortic.* 273, 109645. doi: 10.1016/j.scienta.2020.109645

Guntli, D., Burgos, S., Kump, I., Heeb, M., Pfirter, H.A., and Défago, G.. (1999). Biological control of hedge bindweed (Calystegia sepium) with Stagonospora convolvuli strain LA39 in combination with competition from red clover (Trifolium pratense). *Biol Control.* 15, 252–258. doi: 10.1006/bcon.1999.0726

Hao, A., Marui, A., Haraguchi, T., and Nakano, Y. (2007). Estimation of wet bulb formation in various soils during drip irrigation. *Bulletin of the Faculty of Agriculture, Kyushu University*. 52 (1), 187–193. doi: 10.5109/9304

Havlin, J. L., Tisdale, S. L., Nelson, W. L., and Beaton, J. D. (2016). Soil fertility and fertilizers: An introduction to nutrient management (8th ed.). (New Delhi, India: Pearson Education India).

Hernández-Amasifuen, A. D., Pineda-Lázaro, A. J., and Belba, D.-P. H.. In vitro anther culture of rocoto (Capsicum pubescens Ruiz & Pav.). *Idesia (Arica).* (2022) 40:115–21. doi: 10.4067/S0718-34292022000100115

Hernandez Escareño, J. J. (1998). Inoculación de *Vicia villosa* R. (veza) y *Melilotus alba* M. (trébol dulce) con cepas de *Rhizobium* y su efecto como abonos verdes en la fertilización del suelo [Tesis de maestría]. Universidad Autónoma de Nuevo León, Facultad de Ciencias Biológicas. Monterrey, Nuevo León, México.

Heslop, A. D., Ford, J. L., Jahufer, Z., and Hofmann, R. W. (2025). From root to shoot: morphological evaluation of an international collection of red clover (Trifolium pratense L.) populations. *J. Agron. Crop Sci.* 211, e70055. doi: 10.1111/jac.70055

Hochmuth, B., and Hochmuth, G. (1994). Responses of pepper and watermelon to paper and polyethylene mulches in two spring seasons in north Florida. *Proc. Fla. State Hort. Soc.* 117, 102–104.

Hu, H., Liu, H. Q., Zhang, H., Zhu, J. H., Yao, X. G., Zhang, X. B., et al. (2010). "Assessment of chlorophyll content based on image color analysis: Comparison with SPAD-502." In *2010 2nd International Conference on Information Engineering and Computer Science*. (Wuhan, China: IEEE), 1–3. doi: 10.1109/ICIECS.2010.5678413

Hujerová, R., Pavlů, L., Pavlů, V., Gaisler, J., Hejcman, M., and Ludvíková, V. (2016). Manual weeding of *Rumex obtusifolius* and its effects on plant species composition in organically managed grassland. *J. Pest Sci.* 89, 257–266. doi: 10.1007/s10340-015-0683-x

International Organization for Standardization. (1995). ISO 11261:1995 — Soil quality: Determination of total nitrogen — Modified Kjeldahl method. (Geneva, Switzerland).

Kołota, E., and Adamczewska-Sowińska, K. (2013). Living mulches in vegetable crop production: Perspectives and limitations (a review) *Acta Scientiarum Polonorum Hortorum Cultus* 12, 127–142.

Koudahe, K., Allen, S. C., and Djaman, K. (2022). Revisión crítica del impacto de los cultivos de cobertura en las propiedades del suelo. *Int. Soil Water Conserv. Res.* 10, 343–354. doi: 10.1016/j.iswcr.2022.03.003

Lehmann, P., and Or, D. (2024). Analytical model for bare soil evaporation dynamics following wetting with concurrent internal drainage. *J. Hydrol.* 631, 130800. doi: 10.1016/j.jhydrol.2024.130800

Libreros, D., Zonneveld, M.V., Petz, M., Meckelmann, S.W., Ríos, L., Peña, K., et al. (2013). Catálogo de ajíes (Capsicum spp.) peruanos promisorios conservados en el banco de semillas del INIA-Perú. (Lima, Perú: Instituto Nacional de Innovación Agraria (INIA)).

Lozano Alarcón, C. M. (2012). Serie El punto de ají. Investigaciones en Capsicum nativos. Números 1 y 2. (Lima, Perú: Programa de Hortalizas, Universidad Nacional Agraria La Molina).

Markets and Markets. (2025). Agricultural mulch films market by type (LLDPE, LDPE, EVA, HDPE, and others), application (greenhouse, silage, and mulch) and region—Global forecast to 2029. Available online at: https://www.marketsandmarkets.com/Market-Reports/agricultural-mulch-films-market-741.html (Accessed September 9, 2025).

McEwen, J., and Johnston, A. E. (1985). Yield and nitrogen fixation of Melilotus alba [sweet clover]. *Field Crops Research* 12, 157–172. doi: 10.1016/0378-4290(85)90065-6

McKenna, P., Cannon, N., Conway, J., Dooley, J., and Davies, W.P. (2018). Red clover (Trifolium pratense) in conservation agriculture: A compelling case for increased adoption. *Int. J. Agric. Sustain.* 16, 342–366.

McLean, E. O. (1982). "Soil pH and lime requirement." in Page, A.L. (Ed.), *Methods of soil analysis: Part 2. Chemical and microbiological properties*. 2nd ed.#ed. A. L. Page. (American Society of Agronomy. 199–224. doi: 10.2134/agronmonogr9.2.2ed.c12

Ministerio de Desarrollo Agrario y Riego (MIDAGRI) (2025). *Perfil productivo y competitivo de los principales cultivos del sector. Sistema de Información de Estadísticas Agrarias (SIEA)* (Power BI). Available online at: https://app.powerbi.com/view?r=eyJrIjoiN2U3NTdkYTktOTk5Ny00NjQ5LTg0ZjEtMmIzYzlmZWIwMDhlIiwidCI6IjdmMDg0NjI3LTdmNDAtNDg3OS04OTE3LTk0Yjg2ZmQzNWYzZiJ9 (Accessed March 3, 2025).

Ministerio de Desarrollo Agrario y Riego (MIDAGRI). (2022). Boletín estadístico mensual “El agro en cifras” – 2022. Plataforma del Estado Peruano. Available online at: https://www.gob.pe/institucion/midagri/informes-publicaciones/2826318-boletin-estadistico-mensual-el-agro-en-cifras-2022 (Accessed June 26, 2025).

Mohammadi, G. R., and Mohammadi, G. R. (2012). Living mulch as a tool to control weeds in agroecosystems: A review. *Weed Control.* 29, 75–100. doi: 10.5772/35226

Muhammad, A., Ali, M., Shakeel, M., Buajan, S., and Ali, H. (2022). "Comparative effects of living and non-living mulches on insect pest management in agroecosystems." in Mulching in agroecosystems: *Plants, soil, and environment*, eds. K. Akhtar, M. Aslam, and M. F. Rizwan. (Singapore: Springer Nature Singapore Pte Ltd), 231–248. doi: 10.1007/978-981-19-6410-7_15

Mzabri, I., Rimani, M., Charif, K., Kouddane, N., and Berrichi, A. (2021). Study of the effect of mulching materials on weed control in saffron cultivation in eastern Morocco. *Sci. World J.* 2021, 9727004. doi: 10.1155/2021/9727004

Najul, C., Anzalone, A, Najul, C., and Anzalone, A. (2006). Control de malezas con cobertura vegetal en el cultivo de la Caraota negra (Phaseolus vulgaris L.). *Bioagro* 18 (2), 75–82.

Nesheim, L., and Øyen, J. (1994). Nitrogen fixation by red clover (Trifolium pratense L.) grown in mixtures with timothy (Phleum pratense L.) at different levels of nitrogen fertilization. *Acta Agric. Scand. B Soil Plant Sci.* 44, 28–34. doi: 10.1080/09064719409411254

Nielsen, D. C., and Vigil, M. F. (2005). Legume green fallow effect on soil water content at wheat planting and wheat yield. *Agron. J.* 97, 684–689. doi: 10.2134/agronj2004.0071

Odokonyero, K., Mousa, M. A. A., ElSayed, M. I., Alqurashi, A. D., Gallo, A., and Mishra, H. (2025). Comparative effects of superhydrophobic sand and plastic mulches on growth and yield of sweet pepper (Capsicum annum L.) under arid environments. *HortScience* 60, 87–92. doi: 10.21273/HORTSCI18221-24

Oladosu, Y., Rafii, M. Y., Abdullah, N., Magaji, U., Miah, G., Hussin, G., et al. (2017). Genotype × environment interaction and stability analyses of yield and yield components of established and mutant rice genotypes tested in multiple locations in Malaysia. *Acta Agric. Scand. B Soil Plant Sci.* 67, 590–606. doi: 10.1080/09064710.2017.1321138

Olsen, S. R., and Sommers, L. E. (1982). Phosphorus. *Methods of soil analysis. Part 2. Chemical and microbiological properties.* 9:403–430. doi: 10.2134/AGRONMONOGR9.2.2ED.C24

Overbeck, V., Schmitz-Eiberger, M. A., and Blanke, M. M. (2013). Reflective mulch enhances ripening and health compounds in apple fruit. *J. Sci. Food Agric.* 93, 2575–2579. doi: 10.1002/jsfa.6079

Pederson, G.A., Brink, G.E., and Fairbrother, T.E.. (2002). Nutrient uptake in plant parts of sixteen forages fertilized with poultry litter: Nitrogen, phosphorus, potassium, copper, and zinc. *Agron. J.* 94, 895–904. doi: 10.2134/agronj2002.8950

Pérez-Grajales, M., González-Hernández, V. A., Mendoza-Castillo, M. C., Peña-Valdivia, C., Peña-Lomelí, A., and Sahagún-Castellanos, J. (2004). Physiological characterization of manzano hot pepper (*Capsicum pubescens* R & P) landraces. *J. Am. Soc. Hortic. Sci.* 129, 88–92. doi: 10.21273/JASHS.129.1.88

Poeplau, C., and Don, A. (2015). Carbon sequestration in agricultural soils via cultivation of cover crops–A meta-analysis. *Agric. Ecosyst. Environ.* 200, 33–41. doi: 10.1016/j.agee.2014.10.024

Puente, G. B., Torres, L. E. E., Hernández, E. F., and Abarca, O. R. (2014). Evaluación técnica, financiera y comercial de los sistemas de producción de Chile manzano (*Capsicum pubescens* RYP) en México. *Anal. Econ.* 29, 209–219.

Quipuscoa Silvestre, V., Tejada Pérez, C., Fernández Ardiles, C., Pauca Tanco, A., Durand Vera, K., and Dillon, M. (2016). Diversidad de Plantas Vasculares de Las Lomas de Yuta, Provincia Islay, Arequipa, Perú, 2016. *Arnaldoa* 23, 517–546. doi: 10.22497/arnaldoa.232.23207

Ratliff, L. F., Ritchie, J. T., and Cassel, D. K. (1983). Field-measured limits of soil water availability as related to laboratory-measured properties. *Soil. Sci. Soc. Am. J.* 47, 770–775. doi: 10.2136/sssaj1983.03615995004700040032x.

Ren, A. T., Zhou, R., Mo, F., Liu, S. T., Li, J. Y., Chen, Y., et al. (2021). Soil Water Balance Dynamics under Plastic Mulching in Dryland Rainfed Agroecosystem across the Loess Plateau. *Agric. Ecosyst. Environ.* 312, 107354. doi: 10.1016/j.agee.2021.107354

Ríos, S., Sánchez-Zamora, M. A., Correal, E., and Robledo, A. (1993). *Melilotus albus* Medicus, una leguminosa de uso múltiple para las tierras calizas de la España seca. *Pastos*, 23(1), 61–76. Unidad de Investigación de Cultivos en Zonas Áridas, Consejería de Agricultura, Ganadería y Pesca de Murcia; INGEMISA, Murcia, España.

Sahmat, S. S., Rafii, M. Y., Oladosu, Y., Jusoh, M., Hakiman, M., and Mohidin, H. (2024). Unravelling the dynamics of genotype and environment interactions on chilli (*Capsicum annuum* L.) yield-related attributes in soilless planting systems. *Sci. Rep.* 14, 1698. doi: 10.1038/s41598-023-50381-0

Sánchez Vesga, C., Jaraba, D., Medina, J., Martínez, J., and Martínez, A.. (2003). Requerimientos hídricos del ají dulce (Capsicum annuum L.) bajo riego por goteo en el valle del Sinú medio. *Temas Agrarios.* 8, 11–20.

Sardón Mamani, E. D. (2015). Fortalecimiento de la cadena de valor del rocoto fresco (Capsicum pubescens) de la Selva Central para el mercado de Lima [Tesis de maestría, Universidad Nacional Agraria La Molina]. Repositorio institucional UNALM. Available online at: https://hdl.handle.net/20.500.12996/2071.

Smith, M. (1992). *CROPWAT: A Computer Program for Irrigation Planning and Management* (FAO Irrigation and Drainage Paper 46). (Rome, Italy: Food and Agriculture Organization of the United Nations).

Sokombela, A., Ndhlala, A. R., Bopape-Mabapa, M. P., Eiasu, B. K., Mpai, S., and Nyambo, P. (2025). Colored plastic mulch impacts on soil properties, weed density and vegetable crop productivity: a meta-analysis. *Sci. Rep.* 15, 31891. doi: 10.1038/s41598-025-17237-1

Sran, T. S., Jindal, S. K., and Chawla, N. (2021). Genotype by environment interaction for quality traits in chilli pepper (*Capsicum annuum* L.). *Genetika* 53, 23–49. doi: 10.2298/GENSR2101023S

Stagnari, F., Maggio, A., Galieni, A., and Pisante, M. (2017). Multiple benefits of legumes for agriculture sustainability: an overview. *Chem. Biol. Technol. Agric.* 4, 2. doi: 10.1186/s40538-016-0085-1

Standardization, I. S. O. (1994). *(International O. for ISO 11265:1994 Soil Quality — Determination of the Specific Electrical Conductivity.*

Steinmetz, Z., Wollmann, C., Schaefer, M., Buchmann, C., David, J., Tröger, J., et al. (2016). Plastic mulching in agriculture. Trading short-term agronomic benefits for long-term soil degradation? *Sci. Total Environ.* 550, 690–705. doi: 10.1016/j.scitotenv.2016.01.153

Taylor, N. L., and Quesenberry, K. H. (1996). Red clover science (Vol. 28). (Dordrecht, Netherlands: Springer Science & Business Media).

Teasdale, J. R.. (1996). Contribution of cover crops to weed management in sustainable agricultural systems. *J. Prod. Agric.* 9:475–479. doi: 10.2134/jpa1996.0475

Teasdale, J. R., and Mohler, C. L. (2000). The quantitative relationship between weed emergence and the physical properties of mulches. *Weed Sci. Soc. America* 48, 385–392. doi: 10.1614/0043-1745(2000)048[0385:tqrbwe]2.0.co;2

ISO. (1994). Soil quality –Determination of the specific electrical conductivity (ISO 11265:1994). (Geneva, Switzerland: International Organization for Standardization).

Terpolilli, J. J., Hood, G. A., and Poole, P. S. (2012). “What determines the efficiency of N2-fixing rhizobium-legume symbioses?,” in *Advances in Microbial Physiology*, vol. 60. ed. R. K. Poole. (London, United Kingdom: Academic Press Elsevier), 325–389. doi: 10.1016/B978-0-12-398264-3.00005-X

Terroba, N., Flores M., E., and Cañazaca, E. (2024). Implicancias Del Manejo de Una Pastura Cultivada En Secano y La Respuesta al Abonamiento. *Rev. Investigaciones Altoandinas J. High Andean Res.* 26, 16–23. doi: 10.18271/ria.2024.569

Ţîţei, V. (2022). Some agrobiological peculiarities and the economic value of white sweetclover, Melilotus albus, and yellow sweet clover, Melilotus officinalis, in the Republic of Moldova. *Oltenia J. Stud. Nat. Sci.* 38 (2), 59–67. Museo de Oltenia Craiova.

Thorsted, M. D., Olesen, J. E., and Weiner, J. (2006). Width of clover strips and wheat rows influence grain yield in winter wheat/white clover intercropping. *Field Crops Res.* 95, 280–290. doi: 10.1016/j.fcr.2005.04.001

Trost, B., Prochnow, A., Drastig, K., Meyer-Aurich, A., Ellmer, F., and Baumecker, M. (2013). Irrigation, soil organic carbon and N2O emissions. A review. *Agron. Sustain Dev.* 33, 733–749. doi: 10.1007/s13593-013-0134-0

Walkley, A., and Black, I. A. (1934). An Examination of the Degtjareff Method for Determining Soil Organic Matter and a Proposed Modification of the Chromic Acid Titration Method. *Soil Science.* 37, 29–38. doi: 10.1097/00010694-193401000-00003

Walsh, B. M., and Hoot, S. B. (2001). Phylogenetic relationships of *Capsicum* (Solanaceae) using DNA sequences from two noncoding regions: The chloroplast atpB–rbcL spacer region and nuclear waxy introns. *Int. J. Plant Sci.* 162, 1409–1418.doi: 10.1086/323273

Wang, Z., You, J., Xu, X., Yang, Y., Wang, J., Zhang, D., et al. (2024). Physiological and biochemical responses of melilotus albus to saline and alkaline stresses. *Horticulturae* 10, 297. doi: 10.3390/horticulturae10030297

Wei, X., Garcia-Chevesich, P., Alejo, F., García, V., Martínez, G., Daneshvar, F., et al. (2021). Article hydrologic analysis of an intensively irrigated area in Southern Peru using a crop-field scale framework. *Water (Switzerland)* 13, 1–27. doi: 10.3390/w13030318

Weil, R. R., and Brady, N. C. (2017). *The Nature and Properties of Soil. (15th ed., Global ed.).* (Harlow, England: Pearson Education Limited).

White, C. A., Holmes, H. F., Morris, N. L., and Stobart, R. M. (2016). A review of the benefits, optimal crop management practices and knowledge gaps associated with different cover crop species. Research Review, No. 90. (Warwickshire, UK: Agriculture and Horticulture Development Board (AHDB)).

Williams, M. M., Mortensen, D. A., and Doran, J. W. (1998). Assessment of weed and crop fitness in cover crop residues for integrated weed management. *Weed Sci.* 46, 595–603. doi: 10.1017/s0043174500091153

Wyngaarden, S. L., Gaudin, A. C. M., Deen, W., and Martin, R. C. (2015). Expanding red clover (Trifolium pratense) usage in the corn–soy–wheat rotation. *Sustainability* 7, 15487–15509. doi: 10.3390/SU71115487

Xiao, T., Li, P., Fei, W., and Wang, J. (2024). Effects of vegetation roots on the structure and hydraulic properties of soils: A perspective review. *Sci. Total Environ.* 906, 167524. doi: 10.1016/J.SCITOTENV.2023.167524

Yu, Y., Loiskandl, W., Kaul, H. P., Himmelbauer, M., Wei, W., Chen, L., et al. (2016). Estimation of runoff mitigation by morphologically different cover crop root systems. *J. Hydrol. (Amst.)* 538, 667–676. doi: 10.1016/j.jhydrol.2016.04.060

Zabala, J. M., Marinoni, L., Giavedoni, J. A., and Schrauf, G. E. (2018). Breeding strategies in melilotus albus desr., a salt-tolerant forage legume. *Euphytica* 214, 22. doi: 10.1007/s10681-017-2031-0

Zapana Churata, L. E. (2018). Respuestas a La Crisis Hídrica En Zonas Agrícolas y Urbanas: Caso de Estudio “Proyecto de Irrigación Majes Siguas I” Arequipa – Perú. *Agua y Territorio* 12, 145–156. doi: 10.17561/at.12.3532

Zewdie, Y., and Bosland, P. W. (2000). Evaluation of genotype, environment, and genotype-by-environment interaction for capsaicinoids in *Capsicum annuum* L. *Euphytica* 111, 185–190. doi: 10.1023/A:1003837314929

Zhang, D., Ng, E. L., Hu, W., Wang, H., Galaviz, P., Yang, H., et al. (2020). Plastic pollution in croplands threatens long-term food security. *Glob. Chang. Biol.* 26, 3356–3367. doi: 10.1111/gcb.15043