

The use of hydromulching increases yield and quality of artichoke (*Cynara cardunculus* var. *scolymus*) by improving soil physicochemical and biological properties

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Abstract

We hypothesized that organic liquid mulching formulations called hydromulching can be used in sustainable agricultural production through its direct influence on physicochemical and biological soil properties to improve crop yield and quality. To test this hypothesis, artichoke plants were grown using three hydromulching treatments, rice hulls (RH), wheat straw (WS), and mushroom substrate (MS), and two control treatments, soil covered with polyethylene (PE) and bare soil (BS). Hydromulched soils showed an increase in organic matter, organic carbon, moisture, and mineral contents of K^+ , P, Cu^{2+} , Mn^{2+} , and Zn^{2+} , particularly in the MS-covered soil. Importantly, plant water relationships were superior in all mulching treatments giving rise to the improvement of crop yield and the most important physical quality parameters in artichoke, namely color, firmness, and size. Furthermore, the content of some important nutrient elements in artichoke (K^+ and N) were greater in RH and MS treatments, while sugar concentrations were higher in BS compared to the other treatments. Our data demonstrate that hydromulching is a sustainable alternative to plastic mulching that regulates plant hydric status and soil moisture and fertility, thus improving yield and physical quality characteristics of artichoke heads, and maintaining their chemical and nutritional quality over bare soil.

1 Introduction

One of the most widespread agrotechnology in the Mediterranean area for saving irrigation water is the use of mulching practices, classically performed by plastic films. Several benefits of covering the soil with mulches have been described, such as the reduction of soil evaporation thus preserving soil moisture, suppression of weed growth, control of soil structure and temperature, and influence on soil microbiota (Kruidhof et al. 2009; Steinmetz et al. 2016; Kader et al. 2017; Zhang et al. 2019). Indeed, its importance and applicability are growing very rapidly, as exemplified by a recent study estimating that more than 40% of the regions that are suitable for potato cropping in China with plastic mulching significantly increased food energy per capita (Qin et al. 2022). Besides, the regulation of plant-water relations by means of mulching plays an important role in improving productivity and crop stress resistance (Ozer 2017). However, the environmental problem of the continued use of plastic in agriculture is well known. One of the most negative consequences of the use of plastic mulches is related to handling great amounts of non-degradable and hardly recyclable plastic wastes, and the associated environmental impacts generated (López-Marín et al. 2012). This is likely to pollute the environment either through incineration emissions, landfill leaching, or microplastic residues. Some authors illustrated that microplastics affect soil organic carbon and the microbial community, with the subsequent loss of soil fertility (Ren et al. 2021). Another important limitation of this technology derives from the large amount of resources that must be used for the removal and recycling of cushioning materials, in order to avoid adverse environmental effects. Furthermore, it has been shown that plastics can produce other negative effects on the soil, altering its structure and quality and even accelerating N metabolism (Steinmetz et al. 2016; Chen et al. 2019).

Several authors have reported the benefits of using organic mulching materials, such as straw and grass, to increase soil moisture availability resulting in an increase of crop production (Kader et al. 2017). The use of organic mulches based on straw combined with different tillage practices increased soil moisture retention and decreased temperature (Akhtar, Wang, Khan, Ren, Afridi, et al. 2019). Other authors pointed out a significant increase in soil organic carbon (SOC) on the crop surface, when this treatment with straw mulch was also mixed with other organic components (Zhang et al. 2008; Liu et al. 2016). Additionally, Bana et al.(2018) also showed that the application of organic mulching based on vegetable remains increased the availability of the nutrients N, P, and K, as well as SOC; with substantial improvement in soil fertility. This was explained by the progressive decomposition process of the vegetable organic matter of which the mulch is composed, and by the increase in microbial activity. Likewise, very recently, mulching with straw has been proven to reduce N fertilization needs for dryland wheat production in northern China (Zhao et al. 2022).

Different alternatives have been developed to minimize the environmental and economic impact of plastic mulch. One of these alternatives is the use of hydromulching, which is produced from a mixture of water with a lignocellulosic-type polymer, plus other additives, in such a way that a liquid film is obtained (Claramunt et al. 2020; López-Marín et al. 2021). This material is applied as a paste that covers the surface of the ground and mimics the beneficial effects of traditional plastic mulching. This type of liquid mulching has been applied in reforestation to mitigate runoff and erosion, as well as on slopes to prevent their degradation. At an experimental level, it has been used in fruit crops (Cline et al. 2011) and it has been shown to be an excellent method for weed control in perennials and horticultural crops (Warnick et al. 2006). In preliminary studies, recycled paper pulp combined with different types of industrial by-products such as rice husk, straw, and depleted substrate from mushroom production has proven to be an innovative and effective ecological mulching alternative for horticultural crops (Romero-Muñoz et al. 2019).

Accordingly, the use of ecological and biodegradable soil mulches, derived from industrial or agricultural by-products, is an innovative technology able to maintain or even improve the agronomic benefits of traditional mulching, through its direct influence on the yield and physical quality of the crop and its chemical composition (Kader et al. 2017). Some authors have reported that plastic mulching and other types of organic mulching as wheat straw produced a positive response in horticultural crops by improving soil quality parameters and increasing the yield (Akhtar, Wang, Khan, Ren, Afridi, et al. 2019). Recent studies have demonstrated that the use of straw mulching in a tomato crop enhanced the physical properties of the fruits, as firmness and fruit water content, as well as improved marketable yield (Samui et al. 2020). Kosterna et al. (2010) reported increments in dry matter, reducing sugars (fructose and glucose), and vitamin C in melon as a result of mulching with black polyethylene film. Other studies have reported that the use of organic mulching had a beneficial effect on the synthesis of dry matter, crude fiber, and protein content in pumpkin (Bucki and Siwek 2019). Additionally, the same authors reported increased dry matter content in cucumber fruits of mulched plants, with a similar amount of soluble sugars compared to the fruits from plants grown on non-covered soils.

One of the most important crops in the Mediterranean area is the artichoke. The major production and consumption areas worldwide are located in Spain and Italy. However, the consumption of artichoke has also increased in other locations in the last years, due to its organoleptic, nutritional, and nutraceutical properties. This vegetable stands out due to its very low caloric intake, with only 23 kcal per 100 g (USDA 2021), being ideal to complete a balanced diet. It has a high content of some ions such as K, which is one of the mineral nutrients that the artichoke plants absorb the most during their growth and development, as well as Zn, Mg, and Fe, which are essential for the metabolism of antioxidant stress (Lombardo et al. 2017; Rouphael et al. 2017). To the best of our knowledge, no data have been reported in the literature regarding the effect of hydromulching on soil characteristics that influence crop yield and quality. Therefore, this study aimed at evaluating the use of an innovative and sustainable technique of liquid mulching, called hydromulching, in soil physicochemical and biological properties and its influence on yield and quality characteristics in the artichoke crop in comparison with plastic mulch and non-mulched soil.

2 Material And Methods

2.1 Experimental conditions and plant material

The experimental site was located in Murcia, in the southeastern area of Spain (latitude: 37° 45' N; longitude: 0° 59' W). The climatic data during the growing periods are presented in Table S1. The soil in which the experiment was performed is classified as Haplic Calcisol (USS Working Group WRB 2015). Artichoke seed-grown plants (*Cynara cardunculus* var. *scolymus* L.) cv. Symphony (Nunhens-BASF) were cultivated at a crop density of 0.5 plants per m² three days before the mulching application. A standard Hoagland nutrient solution (NPK) for artichoke was applied through an underground drip irrigation system at a depth of 5 cm, with emitters of 4 L·h⁻¹. Three random cultivation blocks with 30 plants were established with five treatments: three hydromulching treatments with different recycled additives: wheat straw (WS), rice hulls (RH), and substrate used for mushroom cultivation (MS), and two control treatments: two-color low-density polyethylene (PE) and bare soil (BS). The hydromulches employed were applied on the soil surface just before artichoke transplanting as a liquid heterogeneous paste (2 cm thick) that solidified after 24-48h. Artichokes were harvested at the fruiting stage between January and March, and samples from 4 plants per treatment were taken for the analysis of physical and chemical quality characteristics. The collected material was kept at -80°C for further analysis.

2.2 Soil sampling and measurements

Soil moisture (m⁻³·m⁻³) was recorded at 15 cm depth with ECH2O data loggers (Decagon Devices, Pullman, WA, USA). Soil respiration (SR) was measured using a dynamic, closed-chamber SCR-1, and infrared gas analysis system CIRAS-2 (PP System, Amesbury MA, USA). Soil samples (0–20 cm depth) were collected at the end of the experimental period. For soil physicochemical analyses, samples were air-dried and stored at room temperature. Total soil nitrogen (N g kg⁻¹) was analyzed using a combustion nitrogen determinator (LECO FP-528, Leco Corp., St. Joseph, MI, USA). Available phosphorous (P mg kg⁻¹) was determined using the method of Olsen & Watanabe (1954) extracting P with 0.5 M solution of NaCO₃H by photolorimetric determination of the ammonium phosphomolybdate in a UV/VIS spectrophotometer. A saturation paste (34.5% w/w) extract was also obtained from each sample using the procedure outlined by Richards (1954). Electrical conductivity (EC) was determined from the saturation extract. Macronutrient elements K⁺, Na⁺, Ca²⁺, and Mg²⁺ (mg L⁻¹) were analyzed by atomic absorption spectrophotometry (SOLAAR M Series AA Spectrometer, Thermo Scientific, Waltham, MA, USA). Micronutrients including Cu²⁺, Mn²⁺, Fe³⁺, and Zn²⁺ (mg kg⁻¹), were extracted from soil using solutions containing the chelating agent diethylenetriaminepentaacetic acid (DTPA) and then analyzed via

inductively coupled plasma optical emission spectroscopy (ICP-OES, Varian Vista MPX, Palo Alto, CA, USA). Soil anions were also determined from the saturation extract by ion chromatography (METROHM 861 Advanced Compact IC, Herisau, Switzerland) using a METROHM Metrosep CARB1 150/4.0 mm column. Cation exchange capacity (CEC) was extracted with ammonium acetate and determined by atomic absorption spectrophotometry (Sumner and Miller 1996). Soil organic carbon (SOC) and soil organic matter (SOM) were determined by dichromate oxidation in acid medium following the method of Walkley & Black (1934). The composition and properties of the hydromulches were determined with the same methods used for the soil samples, and the data are shown in Table S2. All analyses were run in at least four replicates.

2.3 Yield and physical quality characteristics of artichoke heads

Artichokes were harvested weekly between January and March and marketable yield (kg m^{-2}) was determined. An artichoke head was considered valid for counting as marketable yield when its diameter was higher than 7 cm and did not present any tipburn and/or open bracts. Fully artichoke heads were harvested and their fresh weight (FW), length, and width were registered. Then, a piece of the edible part was weighed and lyophilized for 120 h at -55°C (Christ Alpha 1–2 LDplus, Osterode am Harz, Germany) to determine the water content (WC) using the following equation:

$$\frac{FW(g) - DW(g)}{FW(g)} \times 100$$

Firmness was measured using a TA-XT2i texturometer (Stable Micro Systems, Godalming, UK), validated for tensile, compression, and flexure tests following the methodology of Martínez-Esplá et al. (2017). Three color measurements on different points of external bracts of artichoke heads were performed in the CIELAB ($L^* a^* b^*$) color space using a Minolta CR-300 Chroma Meter (Minolta Camera Co. Ltd, Osaka, Japan). The measuring aperture diameter was 8 mm and the instrument was calibrated with Minolta standard white plate before sampling globe artichoke heads. L^* (lightness, ranging from 0 (black) to 100 (white)), a^* (ranging from -60 (green) to $+60$ (red)), and b^* (ranging from -60 (blue) to $+60$ (yellow)) readings were transformed to those of the L, a, b color space.

2.4 Chemical quality parameters of artichoke heads

2.4.1 Mineral composition

Anion and cation concentrations (mg kg^{-1} DW) were determined in freeze-dried edible parts. The anions were extracted with DI water and subsequently measured by ion chromatography (METROHM 861 Advanced Compact IC, Herisau, Switzerland), using a METROHM Metrosep CARB1 150/4.0 mm column. The cations were extracted by acid digestion, using an ETHOSONE microwave digestion system (Milestone Inc., Shelton, CT, USA), and analyzed by inductively-coupled plasma optical emission (ICP-OES, Varian Vista MPX, Palo Alto, CA, USA).

2.4.2 Total protein content

The total nitrogen (mg g^{-1} DW) was analyzed in freeze-dried edible parts using a combustion nitrogen determinator (LECO FP-528, Leco Corp., St. Joseph, MI, USA). Nitrogen analyses were carried out in four replicates. Following Jones et al (1942), a conversion factor of 6.25 was used to convert total nitrogen to total protein (mg g^{-1} DW).

2.4.3 Sugar content

The concentrations of sugars glucose, fructose, and sucrose (mg g^{-1} DW) were determined using the methodology described by Albacete et al. (2015) with some modifications. Briefly, 1 mL of extraction buffer (methanol/water, 80/20, v/v) was added to 50 mg of previously freeze-dried and ground samples. The samples were homogenized and incubated at 4°C for 30 min, with shaking. After incubation, they were centrifuged at 20.000 g and 4°C for 15 min. The supernatant was passed through C18 solid-phase extraction columns (Sep-Pak, Waters, Milford, MA, USA) to remove interfering macromolecules. The analysis was carried out by ion chromatography using a 817 Bioscan (Metrohm, Herisau, Switzerland) system equipped with a pulsed amperometric detector (PAD) and a gold electrode. The column used was a METROHM Metrosep Carb 1-150 IC column (4.6×250 mm), which was heated to 32°C .

2.5 Statistical analysis

The normal distribution and the common variance of the experimental error were verified through Shapiro–Wilk and Bartlett's tests, respectively. The significance of the treatment effects was determined by analysis of variance (ANOVA), and the significance ($P \leq 0,05$) of the differences between mean values was tested by Tukey's honestly significant difference (HSD) test using SPSS (IBM SPSS Statistics 25.0, Chicago, IL, USA). All variables were subjected to a principal component analysis (PCA) to explore relationships among variables and treatments. The PCA outputs include variable loading to each selected component and treatment component scores.

3 Results

3.1 Soil quality-related parameters

Tables 1 and 2 and Figure 1 show the soil quality-related parameters (physicochemical and biological) analyzed in the control and hydromulching treatments. Regarding soil physicochemical characteristics, it is noteworthy to point out that all mulching treatments reduced EC, being PE and WS those which presented the lowest values, with a decrease of 46% and 34%, respectively (Table 1). CEC was also influenced by the use of mulching, being significantly higher in all mulching treatments (by 20% on average) with respect to the bare soils. Importantly, soil moisture was also higher in all cover treatments compared to bare soil (Figure 1a). In general, the use of organic mulches also affected soil mineral composition as shown in Table 2. Notably, soils mulched with the plastic film presented a general depletion of the macro and micronutrients compared to non-mulched soils, but no significant differences were observed. The macronutrients K^+ and P increased by 15% and 40% on average, respectively, in the MS- and RH-hydromulched soils compared with bare soil. Additionally, a significant increase of Mn^{2+} and Zn^{2+} was observed particularly in soils hydromulched with MS (by 35% and 37%, respectively). Despite being non-significant, there existed a trend to decrease the toxic ions Cl^- and Na^+ in all mulching treatments, which was more apparent in the hydromulched soils (Table 2).

All biological properties of the soil, which are important indicators of soil health, were positively affected by the mulching treatment. Both SOM and SOC increased significantly in all mulching treatments compared to bare soil, especially in the hydromulching treatments (by 60% on average, Figure 1b-c). Similarly, the C:N ratio was significantly superior in the mulching treatments, with WS showing the highest values (by 82% higher than those of bare soil, Table 1). Importantly, the behavior of soil respiration was strongly affected by mulching, provoking a sharp increase in all treatments, especially acute in the soil covered with PE (by 7.5-fold compared to bare soil).

3.2 Yield-related parameters

The use of mulching influenced yield-related parameters of artichoke plants regardless of the type of mulching. All mulching treatments significantly increased marketable yield (by 40% on average) with respect to the bare soil (Figure 2a). Importantly, this yield increase observed in plants grown in mulched soils was due to a significant increase in both head FW (Figure 2b) and the number of artichokes per plant (Figure 2c).

3.3 Physical quality parameters

To study the effect of mulching on the physical characteristics of artichoke, the most important physical quality parameters in this crop were evaluated: edible part WC and FW, and head length, width, firmness, and color parameters (Table 3). All the mulching treatments significantly increased edible part WC (by 55%) and FW (by 70%) with respect to the bare soil (Table 3). Interestingly, compared to bare soil, head firmness increased significantly only in plants subjected to hydromulching treatments but not to the PE treatment. Head length and width increased significantly with the mulching treatment except for head length in WS-treated plants, which did not vary significantly compared to bare soil (Table 3). The outer bract color is one of the physical characteristics of globe artichoke that strongly influence consumer preference. The a^* color parameter (greenness) was significantly deeper in heads of artichokes subjected to the RH treatment compared to the other treatments, while the b^* color parameter (yellowness) significantly increased in RH-, WS-, and PE-treated artichokes. The brightness parameter (L^*) was not significantly affected by the mulching treatment (Table 3).

3.4 Chemical quality parameters: mineral profile and sugar and protein content

Table 4 exhibits the mineral nutrient profile of artichoke heads, being N, K⁺, and P⁵⁺ the most abundant elements. In general, no significant differences were observed among treatments for any mineral nutrient analysed, with the only exception of a significant reduction K⁺ concentration in the PE-mulched artichokes and a significant decline of Cl⁻ in the heads of mulched artichoke plants (Table 4). Regarding sugar content, PE treatment reduced significantly the concentrations of glucose and fructose compared to non-mulched plants, whereas the hydromulching did not affect the concentrations of these two hexoses (Figure 3a-b). However, all mulching treatments, except MS-treatment, significantly reduced sucrose concentrations of artichoke heads compared to bare soil (Figure 3c). Likewise hexoses, protein content was not influenced by the hydromulching treatments, but it was significantly reduced in heads of artichoke plants mulched with PE (Figure 3d).

3.5 Principal Component Analysis

A score PCA was performed to obtain the scores of the individual plants within each hydromulching treatment. The score values were represented using a bi-plot (Figure 4a), which separated and categorized the treatment populations into five groups. The score PCA revealed a clear separation of the scores of artichoke plants grown in bare soil from plants grown in mulched soil. Importantly, the scores of the hydromulching treatments were also well differentiated from the PE treatment, especially MS and RH (Figure 4a).

Further, to reduce the dimensionality of the set of data and to statistically identify the most important artichoke quality parameters and their associations affected by the different mulching strategies, a loading PCA was performed (Figure 4b). This unsupervised clustering method preserved most of the statistical variance. Indeed, the first 3 principal components (PCs) were associated with eigenvalues greater than 10 and explained 70.93% of the total variance (data not shown), with PC1 accounting for 36.14% and PC2 for 21.4%. The loading plot revealed that most of the variables of this study clustered within PC1. From them, fruit yield and important soil (SOM, SOC, SR), physical (edible part FW, and head length, width, and firmness), and chemical (protein content, N, K⁺, Mg²⁺, and P⁵⁺) quality parameters were positively and strongly associated (>0.6) with PC1 (Figure 4b). In contrast, soil EC, fructose, sucrose, and Cl⁻ were negatively associated with PC1.

4 Discussion

Many studies have stated the beneficial effects of soil mulching on minimizing the deterioration of agricultural soils, thus improving crop yield and the physicochemical quality of foods of plant origin (Jordán et al. 2010; Kader et al. 2017). The experimental area where this study was performed is located in the western part of the Mediterranean basin that faces important problems associated with climate change, such as temperature increase and erratic rainfall regimes compared to the average time series (Table S1), leading to soil salinization and fertility loss. In this study, all mulching treatments reduced EC (Table 1), and thus, soil salinity, as previously reported by Rhaman et al. (2006), who confirmed that mulching practice was an effective technology to reduce salinity and conserve humidity in the rootzone. Besides, considering that the levels of the chemical elements of the three hydromulching formulations tested in this study were remarkably higher than those of the soil (Table S2), the increased concentration of some mineral elements in the hydromulched soils (Table 2) could be explained by their release from the hydromulching material. This boost in soil fertility by the organic mulching has been also reported by other authors. Fan et al. (2005) showed a net positive K⁺ and P balance and higher availability of these nutrients in soils covered with straw mulch in comparison with soils mulched with plastic, while (Akhtar, Wang, Khan, Ren, Afridi, et al. 2019) reported that the addition of crop residues to the soil surface increased nutrient concentration and availability. Our results also show that the use of mulching improved the content of SOM and SOC, especially in hydromulched soils (Fig. 1b-c). Furthermore, the changes in soil quality characteristics induced by mulching were associated with yield improvement of artichoke plants since these parameters clustered together in the loading PCA (Fig. 4b). This fact is very relevant because SOC is the main component of SOM and an indicator for soil health, and it has been associated with improved food production and adaptability to climate change, through water and soil fertility maintenance (FAO 2017; Garratt et al. 2018; Oldfield et al. 2018; Oldfield et al. 2019). Importantly, SR, which is a biological-related soil parameter, increased in all mulching treatments (Table 1) and clustered with crop yield (Fig. 4b). This suggests a global rise in microbial activity of mulched soils due to the higher availability of energy released from the decomposition of organic matter and the increase in soil moisture (Fig. 1a). Indeed, it has been demonstrated that the mulching technique affects the hydrothermal regime of soils by increasing soil temperature and reducing soil-water evaporation (Kader et al. 2017). Additionally, microbial respiration is limited by hydric stress (Liu et al. 2009), so an increase in soil moisture favors greater soil respiration, and therefore higher SOC and SOM content, as observed in this study (Fig. 1b-c).

Further, our work revealed that the use of mulching, and specifically, sustainable hydromulching, also improved the hydric and physical quality characteristics of artichokes, through changes in soil parameters (Table 3, Fig. 4b). It has been previously shown that plastic mulching influenced the growth of artichoke plants and increased the physical quality of their heads (Leskovar et al. 2013). Besides, some studies associate the use of biodegradable mulches with productivity and quality improvement in different vegetable crop species, such as tomato, cucumber, pumpkin, and watermelon (Bucki and Siwek, 2019). Other studies related the firmness and color of tomato fruits with the use of biodegradable (Sekara et al. 2019) or inorganic (Ozer 2017) mulches.

Despite some alternative mulching materials have been assayed in terms of crop quality improvement (Cline et al. 2011; Akhtar et al. 2019b), no studies have addressed so far the effect of liquid mulching on nutritional quality components of vegetable crops. We found that some important mineral nutrients in artichokes clustered with soil quality characteristics (Fig. 4b), thus suggesting that (hydro)mulching modified artichoke head mineral composition by affecting soil parameters. Various authors have reported that the food quality of vegetable crops is influenced by soil characteristics and crop management technologies (Chung et al. 2017). There existed a trend in artichoke plants grown in soils mulched with PE, which showed a general depletion in the mineral composition of their capitula (Table 4). This mineral content decline can be explained by inefficient temperature regulation, as stated for synthetic mulches (Chalker-Scott 1962; Kader et al. 2019; Iqbal et al. 2020) and/or by pH imbalance occurred in soils covered with the inorganic mulches (Iles and Dosmann 1998; Khurshid et al. 2014). In contrast, hydromulching treatments, particularly RH and MS, tended to generally increase the mineral composition of artichoke heads (Table 4). Among all mineral nutrients analysed, the hydromulching effect on K^+ levels was especially noticeable. This is in line with other studies reporting that K^+ was one of the most abundant macronutrient in artichoke, likely because of its high root absorption and shoot translocation rates (Colla et al. 2013; Lombardo et al. 2017; Rocchetti et al. 2020). Additionally, our study revealed significantly higher K^+ concentrations in all mulched artichoke heads than those reported in earlier studies (Pandino et al. 2011; Lombardo et al. 2017; Gagliardi et al. 2020; USDA 2021). However, Na^+ concentrations were notably lower than those found by other authors in artichokes, where Na^+ levels were even higher than Ca^{2+} levels (Romani et al., 2006). The shift of Na^+/Ca^{2+} balance compared to other studies can be attributed to the type of soil where the study was conducted, classified as Haplic Calcisol (USS Working Group WRB 2015). Besides, Cl^- concentrations dropped in mulched artichokes. The reduced Na^+ and Cl^- content in artichoke as a consequence of the mulching practise could have important implications for human health, since these ions are involved in increased blood pressure and cardiovascular disease risk (Martínez-Ballesta et al. 2010; Emmerik et al. 2020; Moradi et al. 2021).

From all elements analyzed, N was the most abundant in artichoke heads (Table 4), since it is a mineral nutrient and a component of many organic molecules, such as proteins (el Sohaimy 2014; Otálora et al. 2018). Our findings on artichoke protein concentrations resembled other studies (Rouphael et al. 2017; Gagliardi et al. 2020). Importantly, protein content clustered with soil quality parameters in the loading PCA (Fig. 4b). Thus, RH and MS hydromulching treatments increased total protein concentrations of artichoke heads with respect to the PE-treatment (Fig. 3d). Despite hydromulching provoked a general increase in the mineral nutrient and protein concentrations of artichokes, sugar concentrations were not affected or even decreased with hydromulching (Fig. 3a-c). Besides, artichoke plants grown on bare soil presented the lowest water retention (Fig. 1a, Table 3), thus greater exposure to water limitation in the soil. In the case of the Mediterranean region, the water limitation has been even more accentuated due to its location with extremely irregular rainfall regimes (Table S1). One of the mechanisms that plants use to combat the harmful effects provoked by water stress is to synthesize different kinds of protective compounds, such as compatible solutes and secondary metabolites (Chen and Murata 2002; Peshev and Ende 2013). Sucrose is thought to be a compatible solute and it is synthesized in response to osmotic stress by definition and can occur at high intracellular concentrations without interfering with normal cellular metabolism (Peters et al. 2007; Farrant and Moore 2011; Zhang et al. 2018). Thus, the accumulation of sugars (mainly sucrose) in the heads of artichoke plants grown on bare soil (Fig. 3c) can be explained by the adjustment of its water relations through osmoregulation due to transient hydric stress episodes.

5 Conclusions

The results of this study altogether demonstrate that hydromulching improved soil physicochemical and biological parameters, thus inducing a better water status of artichoke plants. This has been shown to have a direct implication on the improvement of the artichoke crop productivity and physical quality characteristics of the heads. Furthermore, the hydromulch treatments, especially MS and RH, were more sustainable than PE in terms of soil fertility and nutrient cycling, provoking a general increase in artichoke head mineral content, while sugars decreased with respect to bare soil. This can be attributed to lower water retention of bare soil thus

generating transient water stress that induced adaptative responses, such as sugar accumulation. It can be concluded that hydromulching is an innovative, ecological, and sustainable technique for increasing yield and quality in artichoke crop production through improved resource use efficiency. This technique will be of utmost applicability for improving food provision and security in (semi)arid regions, such as the Mediterranean agrosystem, where soil degradation and water scarcity are central problems.

Declarations

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Disclosure statement

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Author Contributions

Alfonso Albacete, Francisco M. del Amor, and Josefa López-Marín contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Miriam Romero-Muñoz, Amparo Gálvez, and Alfonso Albacete. The first draft of the manuscript was written by Alfonso Albacete and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript

Data Availability

All data will be available under reasonable request to the corresponding author.

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Tables

ble 1. Physicochemical and biological parameters of soils uncovered and covered with different types of ilches.

atments	Physicochemical parameters		Biological parameters	
	EC (dS m ⁻¹)	CEC (meq 100g ⁻¹)	C:N	SR (μmol CO ₂ m ⁻² s ⁻¹)
BS	1.47 ± 0.10 ^a	8.60 ± 0.26 ^b	7.64 ± 0.25 ^b	2.22 ± 0.88 ^c
PE	0.79 ± 0.02 ^b	10.66 ± 0.17 ^a	12.90 ± 0.86 ^a	16.65 ± 1.95 ^a
MS	1.18 ± 0.19 ^{ab}	10.97 ± 0.74 ^a	10.26 ± 1.40 ^{ab}	12.25 ± 0.73 ^{ab}
RH	1.17 ± 0.02 ^{ab}	9.41 ± 0.08 ^{ab}	12.93 ± 1.04 ^a	8.04 ± 0.61 ^b
WS	0.96 ± 0.10 ^b	10.92 ± 0.42 ^a	13.93 ± 0.98 ^a	10.64 ± 1.16 ^b

data are expressed as mean ± standard error, n = 4. Different letters within a column indicate significant differences among treatments according to Tukey’s HDS test (P ≤ 0.05). BS: bare soil; PE: polyethylene; MS: mushroom substrate; RH: rice hulls; WS: wheat straw; EC: ctrical conductivity; CEC: cation exchange capacity; C:N: carbon to nitrogen ratio; SR: soil respiration.

able 2. Mineral nutrient concentrations in soils uncovered and covered with different types of mulches.

Treatments	N (g kg ⁻¹)	P (mg kg ⁻¹)	K ⁺ (mg L ⁻¹)	Mg ²⁺ (mg L ⁻¹)	Ca ²⁺ (mg L ⁻¹)	SO ₄ ²⁻ (mg L ⁻¹)
BS	0.87 ± 0.01 ^a	25.15 ± 2.95 ^a	54.67 ± 7.58 ^a	38.00 ± 5.67 ^a	137.01 ± 20.05 ^a	299.74 ± 56.38 ^a
PE	0.63 ± 0.03 ^a	23.58 ± 2.74 ^a	36.57 ± 1.92 ^a	30.33 ± 8.31 ^a	106.97 ± 28.66 ^a	197.21 ± 65.69 ^a
MS	0.92 ± 0.12 ^a	35.23 ± 5.71 ^a	62.00 ± 12.90 ^a	37.17 ± 4.10 ^a	178.00 ± 24.31 ^a	406.37 ± 71.10 ^a
RH	0.78 ± 0.08 ^a	32.24 ± 4.22 ^a	59.83 ± 3.38 ^a	38.47 ± 4.30 ^a	170.97 ± 18.77 ^a	468.37 ± 51.12 ^a
WS	0.71 ± 0.08 ^a	31.73 ± 2.89 ^a	45.63 ± 9.29 ^a	29.53 ± 4.12 ^a	133.03 ± 18.80 ^a	322.08 ± 81.15 ^a

Fe ²⁺ (mg kg ⁻¹)	Cu ²⁺ (mg kg ⁻¹)	Mn ²⁺ (mg kg ⁻¹)	Zn ²⁺ (mg kg ⁻¹)	Cl ⁻ (mg L ⁻¹)	Na ⁺ (mg L ⁻¹)	
BS	3.30 ± 0.10 ^{ab}	1.96 ± 0.19 ^{ab}	9.78 ± 0.71 ^b	2.73 ± 0.34 ^b	223.74 ± 21.27 ^a	129.23 ± 11.21 ^a
PE	2.85 ± 0.14 ^b	1.77 ± 0.15 ^b	7.61 ± 0.35 ^c	2.23 ± 0.21 ^b	180.38 ± 45.35 ^a	114.00 ± 17.11 ^a
MS	4.78 ± 0.26 ^a	2.41 ± 0.02 ^a	13.31 ± 0.10 ^a	3.75 ± 0.10 ^a	167.06 ± 14.04 ^a	103.90 ± 6.28 ^a
RH	3.27 ± 0.13 ^{ab}	2.15 ± 0.17 ^{ab}	9.25 ± 0.56 ^{bc}	2.78 ± 0.23 ^b	125.05 ± 18.19 ^a	93.93 ± 9.95 ^a
WS	3.70 ± 0.15 ^b	1.97 ± 0.04 ^{ab}	11.18 ± 0.19 ^b	2.45 ± 0.08 ^b	133.72 ± 2.39 ^a	103.17 ± 2.75 ^a

All data are expressed as mean ± standard error, n = 4. Different letters within a column indicate significant differences among treatments according to Tukey's HSD test (P ≤ 0.05). BS: bare soil; PE: polyethylene; MS: mushroom substrate; RH: rice hulls; WS: wheat straw.

Table 3. Physical and quality characteristics in heads of artichoke plants (cv. Symphony) grown on uncovered and covered soils with different types of mulches.

Treatments	FW ^{edible part} (g)	WC ^{edible part} (%)	Firmness (N)	Length (cm)	Width (cm)	L*	a*	b*
BS	43.03 ± 13.63 ^b	42.45 ± 0.10 ^b	13.54 ± 0.10 ^b	8.59 ± 0.10 ^b	7.03 ± 0.06 ^b	54.58 ± 0.55 ^a	-5.25 ± 0.50 ^a	22.44 ± 0.12 ^b
PE	70.25 ± 12.42 ^a	64.10 ± 0.11 ^a	16.20 ± 0.11 ^{ab}	9.47 ± 0.11 ^a	7.80 ± 0.14 ^a	53.68 ± 0.40 ^a	-6.27 ± 0.09 ^{ab}	24.38 ± 0.41 ^a
MS	63.76 ± 4.39 ^a	65.12 ± 0.09 ^a	18.59 ± 0.09 ^a	9.60 ± 0.09 ^a	7.57 ± 0.18 ^a	53.88 ± 0.02 ^a	-5.44 ± 0.12 ^a	22.44 ± 0.41 ^b
RH	69.42 ± 6.79 ^a	64.71 ± 0.10 ^a	19.78 ± 0.10 ^a	9.51 ± 0.10 ^a	7.77 ± 0.09 ^a	55.92 ± 0.73 ^a	-6.61 ± 0.09 ^b	25.34 ± 0.71 ^a
WS	67.02 ± 6.52 ^b	65.25 ± 0.08 ^a	18.55 ± 0.08 ^a	8.95 ± 0.08 ^b	7.59 ± 0.25 ^a	53.66 ± 0.57 ^a	-5.94 ± 0.28 ^{ab}	24.80 ± 0.28 ^a

All data are expressed as mean ± standard error, n = 9. Different letters within a column indicate significant differences among treatments according to Tukey's HSD test (P ≤ 0.05). BS: bare soil; PE: polyethylene; MS: mushroom substrate; RH: rice hulls; WS: wheat straw; FW: fresh weight; WC: water content; L*, a*, and b*: CIELab color parameters.

Table 4. Mineral nutrient concentrations in heads of artichoke plants (cv. Symphony) grown on uncovered and covered soils with different types of mulches..

Treatments	N (mg g ⁻¹ DW)	P ⁵ (mg kg ⁻¹ DW)	K ⁺ (mg kg ⁻¹ DW)	Mg ²⁺ (mg kg ⁻¹ DW)	Ca ²⁺ (mg kg ⁻¹ DW)	SO ₄ ²⁻ (mg kg ⁻¹ DW)
BS	21.82 ± 3.16 ^a	2.72 ± 0.33 ^a	16.18 ± 1.19 ^{ab}	1.29 ± 0.08 ^a	1.22 ± 0.28 ^a	0.53 ± 0.05 ^a
PE	16.13 ± 0.86 ^a	2.13 ± 0.19 ^a	12.81 ± 0.89 ^b	1.19 ± 0.12 ^a	1.14 ± 0.39 ^a	0.49 ± 0.02 ^a
MS	23.03 ± 0.66 ^a	2.64 ± 0.09 ^a	16.04 ± 0.60 ^{ab}	1.36 ± 0.02 ^a	1.15 ± 0.13 ^a	0.65 ± 0.04 ^a
RH	24.18 ± 2.41 ^a	2.94 ± 0.19 ^a	17.68 ± 1.21 ^a	1.42 ± 0.15 ^a	1.22 ± 0.16 ^a	0.55 ± 0.02 ^a
WS	20.26 ± 0.66 ^a	2.43 ± 0.03 ^a	15.97 ± 0.41 ^{ab}	1.24 ± 0.07 ^a	0.61 ± 0.12 ^a	0.68 ± 0.08 ^a

	Fe ²⁺ (mg kg ⁻¹ DW)	Cu ²⁺ (mg kg ⁻¹ DW)	Mn ²⁺ (mg kg ⁻¹ DW)	Zn ²⁺ (mg kg ⁻¹ DW)	Cl ⁻ (mg kg ⁻¹ DW)	Na ⁺ (mg kg ⁻¹ DW)
S	0.064 ± 0.005 ^a	0.062 ± 0.001 ^a	0.014 ± 0.001 ^a	0.023 ± 0.004 ^a	4.42 ± 0.20 ^a	0.43 ± 0.05 ^a
E	0.059 ± 0.004 ^a	0.036 ± 0.004 ^a	0.012 ± 0.001 ^a	0.015 ± 0.003 ^a	2.14 ± 0.14 ^d	0.33 ± 0.03 ^a
MS	0.073 ± 0.007 ^a	0.051 ± 0.001 ^a	0.015 ± 0.001 ^a	0.017 ± 0.003 ^a	3.68 ± 0.10 ^b	0.49 ± 0.07 ^a
RH	0.062 ± 0.003 ^a	0.057 ± 0.007 ^a	0.015 ± 0.001 ^a	0.022 ± 0.002 ^a	3.39 ± 0.18 ^{bc}	0.38 ± 0.04 ^a
WS	0.058 ± 0.006 ^a	0.039 ± 0.002 ^a	0.011 ± 0.001 ^a	0.017 ± 0.001 ^a	2.84 ± 0.03 ^c	0.40 ± 0.04 ^a

l data are expressed as mean ± standard error, n = 9. Different letters within a column indicate significant differences among treatments according to Tukey's HSD test ($P \leq 0.05$).). BS: bare soil; PE: polyethylene; MS: mushroom substrate; RH: rice hulls; WS: wheat straw.

Figures

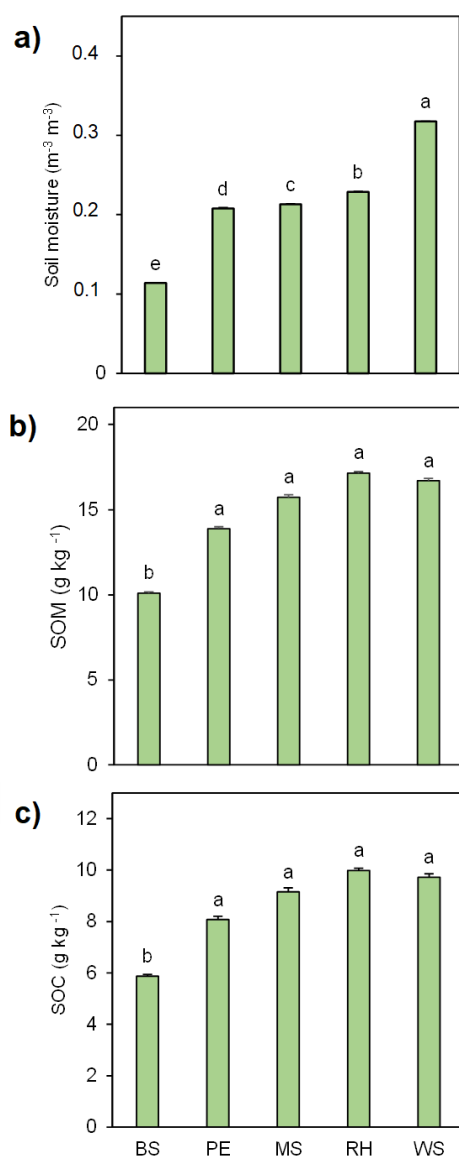


Figure 1

Effect of hydromulching on soil quality characteristics. **(a)** Soil moisture, **(b)** soil organic matter, and **(c)** soil organic carbon content of artichoke plants (cv. Symphony) grown on uncovered soils (BS) or covered with different types of mulches: two-color low-density

polyethylene (PE), rice hulls (RH), wheat straw (WS), and substrate used for mushroom cultivation (MS). All data are expressed as mean $\pm$ standard error, n = 4. Different letters among bars indicate significant differences according to Tukey's HDS test ($P \leq 0.05$).

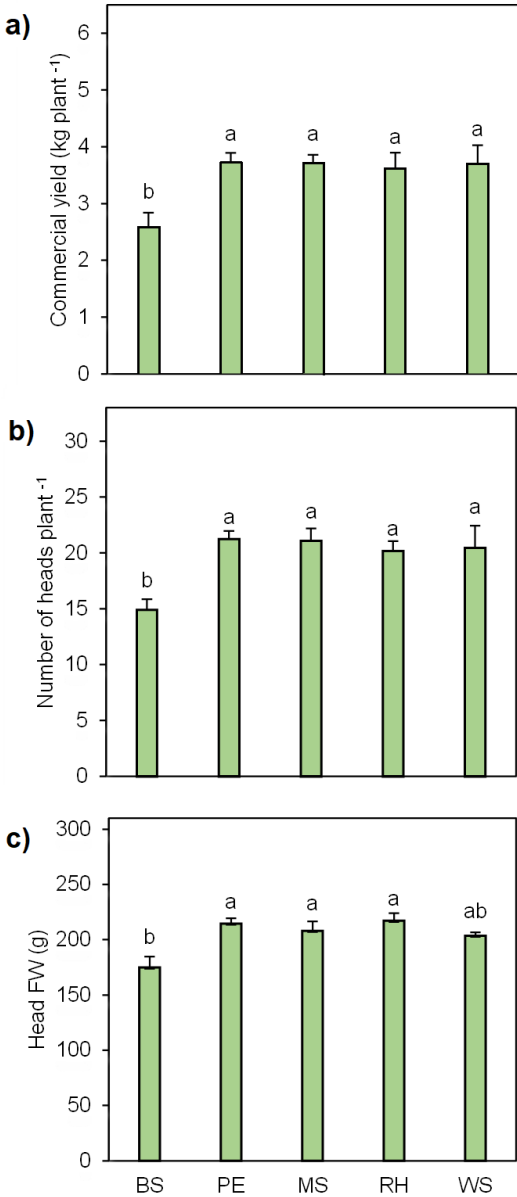


Figure 2

Effect of hydromulching on yield-related parameters of artichoke crop. **(a)** Commercial yield, **(b)** number of artichokes per plant, and **(c)** head fresh weight of artichoke plants (cv. Symphony) grown on uncovered soils (BS) or covered with different types of mulches: two-color low-density polyethylene (PE), rice hulls (RH), wheat straw (WS), and substrate used for mushroom cultivation (MS). All data are expressed as mean $\pm$ standard error, n = 9. Different letters among bars indicate significant differences according to Tukey's HDS test ($P \leq 0.05$).

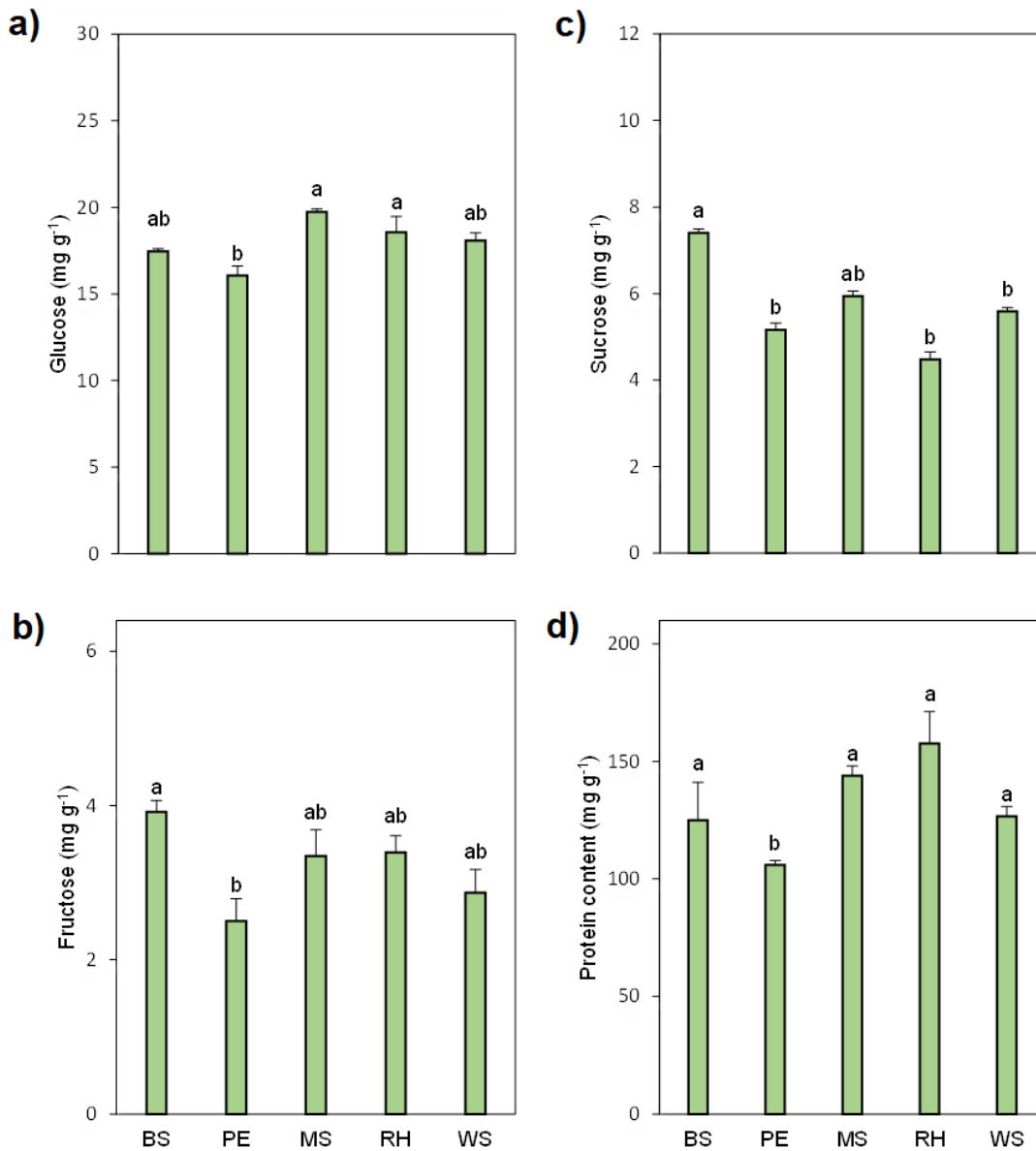


Figure 3

Effect of hydromulching on sugars and protein content of artichokes. **(a)** Glucose, **(b)** fructose, **(c)** sucrose, and **(d)** total protein concentrations in heads of artichoke plants (cv. Symphony) grown on uncovered soils (BS) or covered with different types of mulches: two-color low-density polyethylene (PE), rice hulls (RH), wheat straw (WS), and substrate used for mushroom cultivation (MS). All data are expressed as mean $\pm$ standard error, $n = 4$. Different letters among bars indicate significant differences according to Tukey's HDS test ($P \leq 0.05$).

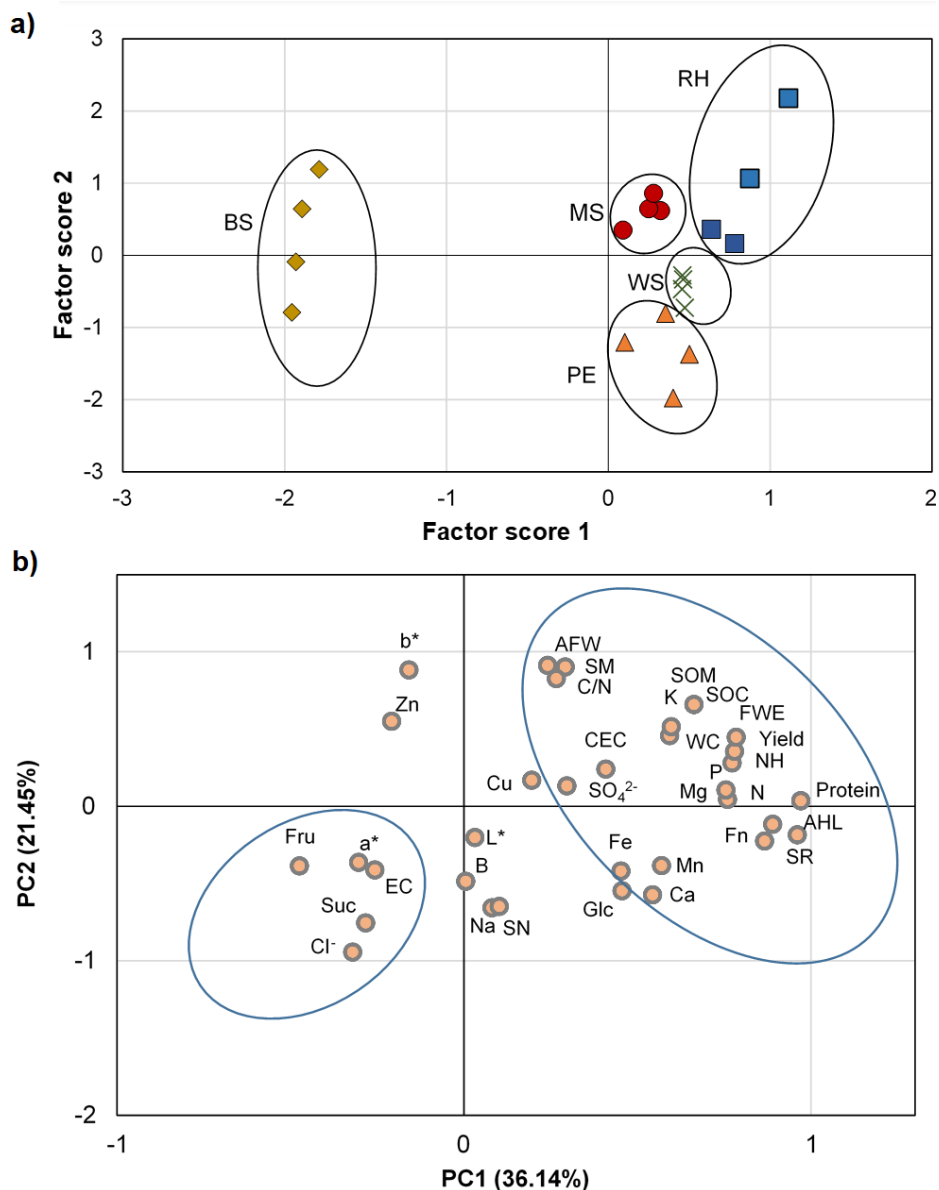


Figure 4

Principal component analysis of hydromulching effects. **(a)** Bi-Plot representing the score values of artichoke plants (cv. Symphony) grown on uncovered soils (BS) or covered with different types of mulches: two-color low-density polyethylene (PE), rice hulls (RH), wheat straw (WS), and substrate used for mushroom cultivation (MS). **(b)** Two axes of a principal component (PC1, PC2) analysis showing the loadings of various soil quality characteristics and yield-related, physical, and chemical quality variables (denoted by abbreviations) of artichoke plants (cv. Symphony) grown on uncovered soils or covered with different types of mulches. Abbreviations used: calcium (Ca^{2+}), copper (Cu^{2+}), iron (Fe^{2+}), potassium (K^{+}), magnesium (Mg^{2+}), manganese (Mn^{2+}), sodium (Na^{+}), phosphorus (P^{5+}), chloride (Cl^{-}), sulfate (SO_4^{2-}), number of heads (NH), head fresh weight (HFW), edible part fresh weight (EFW), head water content (HWC), artichoke head length (AHL), artichoke head width (AHW), firmness (Fn), glucose (Glc), fructose (Fru), sucrose (Suc), soil moisture (SM), soil respiration (SR), soil organic matter (SOM), soil organic carbon (SOC), soil nitrogen (SN), electrical conductivity (EC) and cation exchange capacity (CEC).