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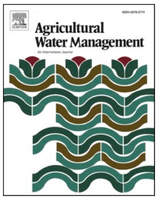

Water footprint and water productivity analysis of an alternative organic mulching technology for irrigated agriculture

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ABSTRACT

Agriculture is causing unprecedented pressure on water resources to meet a growing food demand. This determines the necessity of implementing innovative, sustainable, and measurable systems to decrease water consumption while increasing crop yield. This study analyses the performances of biodegradable mulching (OM) felt for irrigated lettuce, integrating water footprint (WF) and water productivity (WP) assessment. Different types of OM were tested in two farms in the peri-urban area of Florence city (Tuscany, Central Italy) during the cropping seasons 2021 and 2022. Water Productivity has been evaluated using direct measurements, while the WF has been calculated according to ISO 14046. Moreover, the AquaCrop model by FAO has been used to simulate potential optimal irrigation conditions in the two farms. Results show that OM determined smaller water requirements for all the different field configurations and irrigation efficiencies simulated with a reduction ranging between 8 % and 95 %. The results allow to evaluate the relative weight of OM on the overall water consumption of the two farms and provide useful insights on the sustainability of the lettuce production chain helping farmers to identify water-related hotspots.

1. Introduction

Food demand is projected to increase by 35–56 % by 2050 (Van Dijk et al., 2021), with agrifood systems playing a crucial role in ensuring a world free from hunger. Coupling agricultural production efficiency and sustainable use of natural resources is critical in achieving most of the “Sustainable Development Goals” by 2030. (FAO, 2022; Rockström et al.,2020). Water plays a key factor in assuring future food security, with agriculture already accounting for 70 % of global freshwater consumption for its production activities (FAO, 2021; Singh et al., 2022) and global agricultural water scarcity projected to increase due to climate change (Liu et al., 2022).

Alternative agricultural production systems are needed to improve water use efficiency and concurrently increase crop yield (Coluccia et al., 2020; Iglesias and Garrote, 2015; Bonanomi et al., 2017). In Europe, the Common Agricultural Policy (CAP) has been promoting sustainable agriculture water use in the last decades. The CAP has contributed to a decrease in the EU-level agricultural water abstraction by 28 % since 1990 (European Court of Auditors, 2021).

However, agriculture remains the sector with the greatest water consumption in many European Countries. Italian agricultural water withdrawal represents 50 % of the total water withdrawal and half of the total cultivated area is equipped for irrigation (AQUASTAT, 2023), placing Italy among the first European countries to rely on irrigation (ISTAT, 2019). Moreover, at the national level, an overall overuse of water resources can be observed (Fusco et al., 2023), resulting from a combination of reduced rainfall (Caporali et al., 2021) and low technical efficiency in water use for crop production (Laureti et al., 2021).

In this context, applying innovative irrigation water management and technology is fundamental for improving food systems and decreasing agriculture pressure on natural resources. Among water-saving technology, mulching is undeniably a common practice for horticulture farming due to its beneficial effect in controlling soil evaporation, temperature, and weed spread (Ghouse et al., 2020). Mulching is defined as the application of any cover materials on the soil surface (Kasirajan and Ngouajio, 2012). Many studies have confirmed the

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increase of yield due to the mulching positive effect for many crops between a range of 10 %-20 % (Wang et al., 2022, Wang et al., 2020, He et al., 2018, Jabran et al., 2015). Additionally, mulching increases water use efficiency (Wang et al., 2022), shifting the "non-beneficial" water consumption (i.e. soil evaporation) to crop transpiration (Chukalla et al., 2015).

The most common mulching material is polyethylene due to its low cost of production and effectiveness. Indeed, recent studies showed that plastic mulching (PM) can be slightly more effective than other solutions such as Organic Mulching (OM) in increasing crop yield and improving precipitation utilization (Li et al., 2021; Jabran et al., 2015). However, PM fosters the production of greenhouse gasses (GHG) and entails a higher environmental burden due to its production, improper final disposal, and increasing formation of reactive nitrogen form as the higher soil temperature increases microbial activity (Wang et al., 2020, He et al.,2018). On the contrary, OM can assure soil moisture storage increase while reducing GHG emissions compared to PM (Zhao et al., 2019).

Even if the higher cost can be a constraint (Hayes et al., 2019), over the past few years, farmers have gradually moved towards more sustainable materials for implementing mulching (European Commission, 2018; Menossi, 2021). In this context, biodegradable plastic mulch is becoming an alternative due to the lower pollution effect while keeping similar performance of a plastic film (Guerrini et al., 2017).

Introducing proper indicators is essential for a comprehensive evaluation of the performance of different horticultural techniques, as they allow for an objective assessment of both efficiency and sustainability (Montemurro et al., 2018).

Water Productivity (WP) and the Water Footprint (WF) can be valid indicators to deal with agricultural water management multiple dimensions (Fernándes et al., 2020), determining the effectiveness of OM as a water-saving practice and its overall sustainability in terms of water resources use. WP can monitor the increasing food production with increasing water restrictions (Mul et al., 2020), allowing the farmers to compare different irrigation schedules and assess the efficiency of their production system (Molden et al., 2010).

On the other side, WF can provide key information to support agriculture sustainability, quantifying the environmental impacts of agriculture activities by measuring direct and indirect water consumption at multiple scales (D'Ambrosio et al., 2020; Pacetti et al., 2021; Altobelli et al., 2018).

This paper aims at providing a methodological framework to comprehensively assess the performance of different mulching techniques to support farmers management choices, both in terms of improving water productivity within the cropping system and understanding the impact on water resources. WP and WF are used as complementary indicators (Wang et al., 2022; Chukalla et al., 2015 and Li et al.2021) to evaluate the performances of different mulching solutions in two horticultural farms located in central Italy. The indicators are coupled with a crop growth model to evaluate the performance of the mulching under different irrigation scenarios.

Indeed, indicators and crop models are important tools for assessing agricultural systems dynamics under different environmental and management scenarios, which could help farmers in decision-making to improve the sustainability and resilience of their productions (Kephe et al., 2021; Bockstaller et al., 2008; Jones et al., 2017).

However, the active involvement of farmers is fundamental to favour the uptake of innovative solutions (Cramb, 2000). Indeed, this study is part of a broader project called *OrtiBlu* (https://ortiblu.ciatoscana.eu/), which aims to place farmers at the center of the innovation process. The project focuses on evaluating the introduction of water-saving technologies and co-creating experimental designs in real-life contexts. In this study the evidence the results provided in terms of indicators and modelling are integrated with the feedback of farmers, guiding the experimental testing towards the identification of the most appropriate solution (Cramb, 2000).

The paper is structured as follows: description of the experimental site and test design (Section 2.1), case study description, methodology overview including LCA, WP and crop growth model details (Section 2.2) description and interpretation of results in terms of the selected indicators (Section 3), discussion (Section 4) and conclusions (Section 5).

2. Materials and methods

The proposed methodology (Fig. 1) aims at developing a comprehensive assessment of the water related impacts of the entire production chain. Multiple tests were realized using different organic mulching types according to the farmers preferences. The data collected are then used to evaluate the water productivity and to build a WF assessment model according to the ISO 14046. Parallel to this, an AquaCrop model is built to evaluate other cultivation scenarios and their potential effects in terms of WP and WF.

2.1. Experimental site and test design

The performances of the OM were evaluated for two horticulture farms located in Florence peri-urban area (Central Italy). Both farms (Farm 1 and Farm 2 in the hereinafter) are located in the alluvial plain of the Arno River that is characterized by generally deep soils with a silty clayey loam texture (Endoglyi Vertic Cambisoils) and(Corongiu et al., 2016) loamy sandy sediments (Calcaric fluvic Cambisoil) (Gardin and Vinci, 2005) (Fig. 2). The two farms are only 5 km apart and show homogeneous soil texture features. The climatic conditions of the study are typically Mediterranean, characterized by rainy and cold winters, and dry and hot summers with precipitation concentrated in both autumn and spring (Verdi et al., 2022).

Together with the farmers lettuce (Lactuca sativa L.) was selected as testing crop in both farms due to its high economic importance, its water intensity and its high sensitivity to water variability. For both farms and for each crop cycle analysed the field was divided into two adjacent experimental trials to allow the comparison with uniform conditions (climate, plant density, soil, …) of a OM and a no mulching (i.e. Control) cultivation strategy (Fig. 3). The experiments were conducted along two growing seasons, 2021 and 2022.

Table 1 shows the main characteristics and the time of the trials. For the first year of trials, the OM was a biodegradable felt made from recycled materials (OM_1). The weight of the felt differs between the two farms: 800 g m^{-2} for Farm 1 (OM_{1_1}) and 300 g m^{-2} for Farm 2 (OM_{1_2}) according to the preferences expressed by the farmers. Due to its low mechanical resistance, the OM1 mulching film could only be used for a single crop cycle. Therefore, the farmers decided to switch to a different mulching film for the following year's experiment. In the second year, both farms adopted a film made of polylactic acid (PLA) combined with natural fibers (hemp) (OM_2). This biodegradable mulch has been prepared by airlaid technology using natural and bio-based staple fibers. In particular, kenaf, jute and PLA fibers have been feed into air-laid machinery in order to produce at pilot scale (production up to 250 kg/h) airlaid nonwovens. Optimal adhesion among the different fibers layers was ensured by needle punching. The optimal parameters have been established by defining the thickness of the fibers web (2.4 mm) and its weight (450 gr/m^2) according to market available felts; and the homogeneity of the web according to feeding rate keeping a constant fiber blend (70 % natural fibers/30 % PLA based fibers). Each experimental plot was equipped with a dedicated water meter in order to record water volumes used in all the trials.

2.2. Methods

2.2.1. Water productivity

WP can be defined as the ratio of the net benefits from an agricultural system to the amount of water used to produce those benefits (FAO,

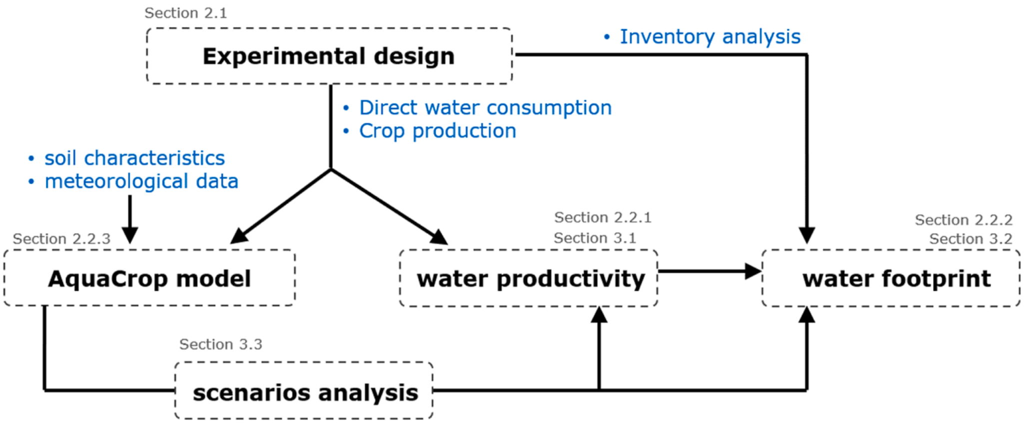

Fig. 1. Methodology flow chart.

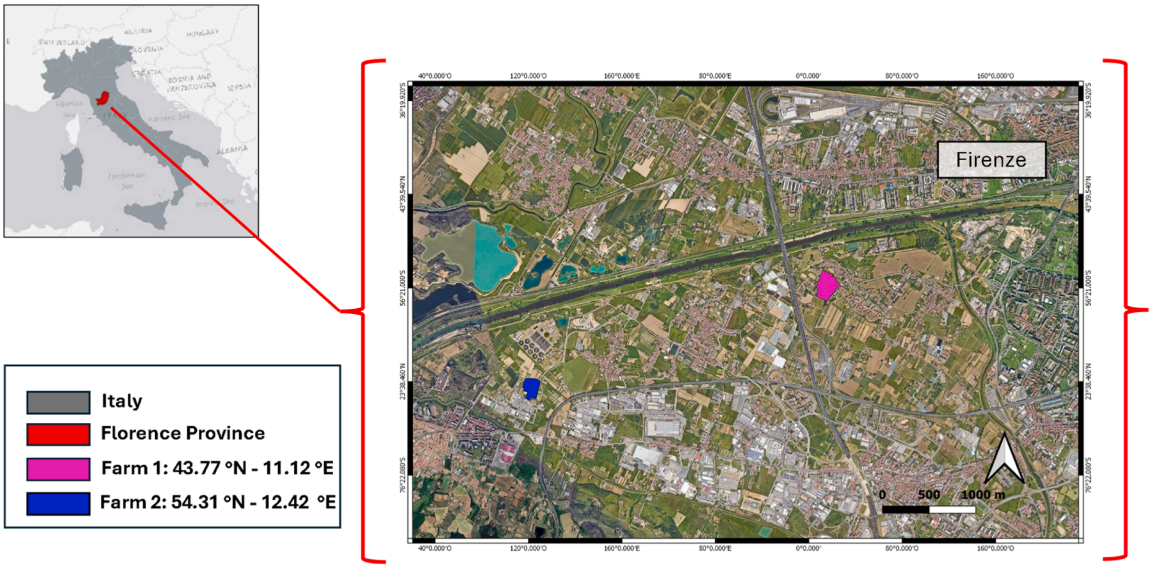

Fig. 2. Study Area: Peri-urban area of Florence municipality (Italy). The pink polygon is the area of Farm 1, while the blue polygon is the area of Farm 2.

2019). WP expressed as kilogram per drop of water (Molden, 1997) is a practical concept to compare water use efficiencies (Villani et al., 2018). In this study, WP was selected to assess the capacity to improve water use efficiency by OM, measuring Irrigation Water Productivity (WP_i) and the Crop Water Productivity (WP_c). The former considered just the irrigation water used (IWU) and the latter the total water used (TWU) (Fernández et al., 2020, Eq. 1).

$$TWU = P_e + IWU \tag{1}$$

Where P_e is the effective rainfall volume for each plant, and IWU is the irrigation water volume for each plant. P_e is assessed removing from the total precipitation P the runoff component (R), evaluated with the curve number (CN) method (Mishra et al.,2003) (Eq.2), which is designed to calculate the runoff generated in a single rainy event but also considering a larger time scale, in this case, the crop cycle of each experiment. The runoff is evaluated for each event and then is summed over the entire crop cycle.

$$R = P - P_e = \begin{cases} 0 for P < I_a \\ \frac{(P - I_a)^2}{P - I_a + S} for P > I_a \end{cases} \tag{2}$$

Q is the amount of generated runoff (mm), P is the precipitation during the crop cycle, S is a site index defined as the maximum storage potential measured using CN of the study plot soil (Eq.3).

$$S = 254 \bullet \left(\frac{100}{CN} - 1\right) \tag{3}$$

Then, WP_c is calculated as the ratio between the average fresh weight of a lettuce plant (Ya, [kg]) along the growing season and the total amount of water consumed by the lettuce(TWU, [m^3]) (Fernández et al., 2020, Eq.4).

$$WP_c = \frac{Ya}{TWU} \tag{4}$$

Instead, WP_i was calculated as the ratio between the average fresh weight of a lettuce plant (Ya, [kg]) and the water volume used for each plant (IW, [m^3]) (Mul et al., 2020; Eq. 5).

$$WP_i = \frac{Ya}{IWU} \tag{5}$$

The significance of these indicators varies. The same lettuce yield can depend not only on the amount of irrigation water used but also on the rainfall available to the crop, which is influenced by the distribution of rainfall throughout the growing season (Pereira et al.,2012).

2.2.2. *Water footprint*

Two main WF assessment approaches have been developed so far.

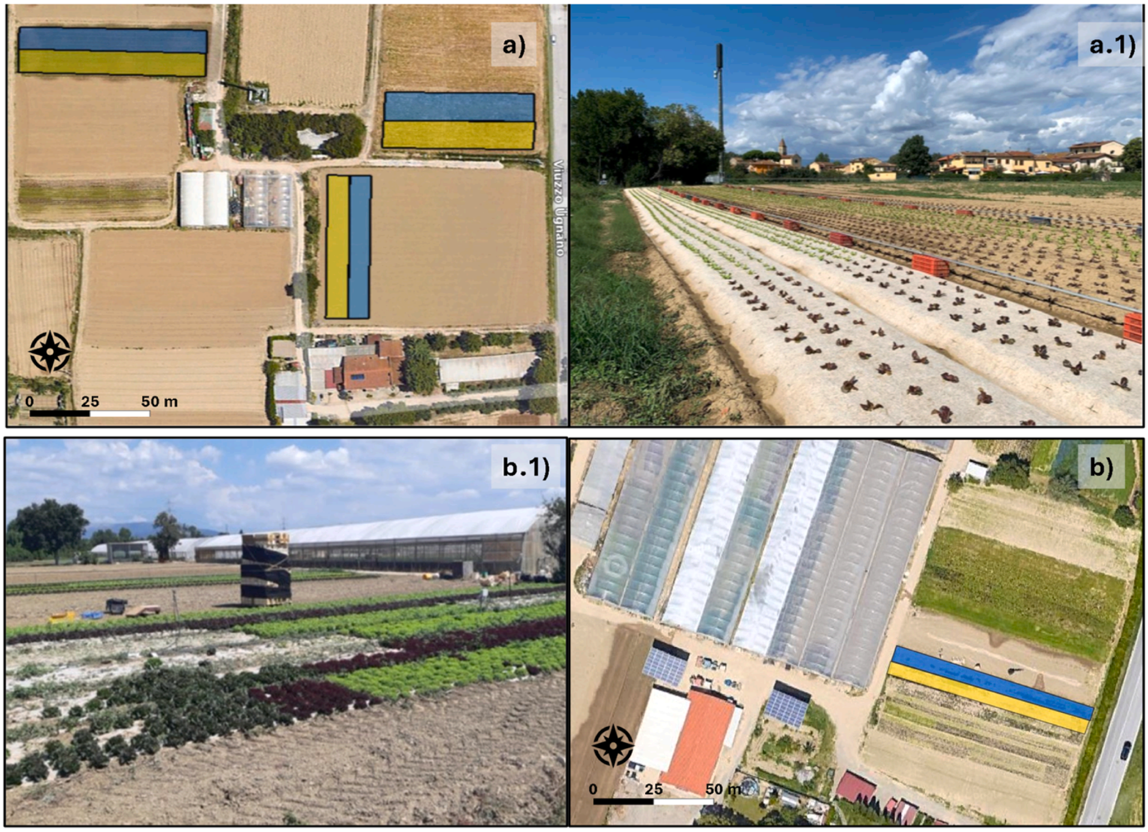

Fig. 3. Experimental sites:a) and a.1) shows the study plot for Farm 1 for both years of trial; b) and b.1) is the study plot of Farm 2 used in both years, the blue rectangle represents the mulching treated lettuce plot and the yellow on the control lettuce plot with bare soil.

Table 1
Experimental Trials characteristic for the Farm1 and Farm2.

TRIALS ID	Transplant date	Trial Area (m^2)	Plant Density (pl m^{-2})	Irrigation System	Mulching type and weight
FARM 1					
AUG_2021_OM_{11}	01/08/2021	336	3000	Micro sprinkler	Recycled (300 g m^{-2})
AUG_2021_C	01/08/2021	336	3000	Micro sprinkler	No mulching (control)
JUL_2022_OM_2	09/07/2022	280	3000	Micro sprinkler	PLA/natural fibers (450 gr/m^2)
JUL_2022_C	09/07/2022	280	3000	Micro sprinkler	No mulching (control)
SEP_2022_ OM_2	01/09/2022	168	4800	Micro sprinkler	PLA/natural fibers (450 gr/m^2)
SEP_2022_C	01/09/2022	168	3600	Micro sprinkler	No mulching (control)
FARM 2					
MAY_2021_OM_{12}	28/05/2021	225	3906	Micro sprinkler	Recycled (800 g m^{-2})
MAY_2021_C	28/05/2021	300	6734	Micro sprinkler	No mulching (control)
JUN_2022_ OM_2	15/06/2022	210	4775	Micro sprinkler	PLA/natural fibers (450 gr/m^2)
JUN_2022_C	15/06/2022	210	5000	Micro sprinkler	No mulching (control)

The first one relies on the definition of WF as a multidimensional indicator (Hoekstra A.Y., 2011) offering a volumetric accounting of water use along an entire production chain and identifying critical hotspots. A second approach was subsequently introduced to assess freshwater-related impacts within the Life Cycle Assessment (LCA) framework (Pfister et al., 2017). The latter was adopted in this study, referring to the methodology formalized by the ISO 140046 (ISO, 2014).

The ISO 14046 reflects the conceptual structure of the LCA (ISO 14044, 2006) and allows the evaluation of the different types of water consumption of a process or product with specific spatial-temporal resolution. The Functional Unit (FU) selected is one kilogram of lettuce. The system boundary is set within the farm production so the analysis can be considered a cradle to farm-gate (Fig. 4)

OpenLCA (Fotia et al., 2021; Zaher et al., 2016) and the Ecoinvent 3.6 (Wernet et al., 2016) database were used to build the models for each trial and calculate the WF.

The Life Cycle Inventory (LCI) was realized taking into account two different phases within the considered system boundaries (all the data used are reported for the functional unit in Table 2 for Farm 1 and Table 3 for Farm 2).

The production of the OM has been characterized in terms of raw materials and energy required for the production. Primary data were collected directly from the producers of the different OMs produced. The OM production is also evaluated in terms of transportation of the

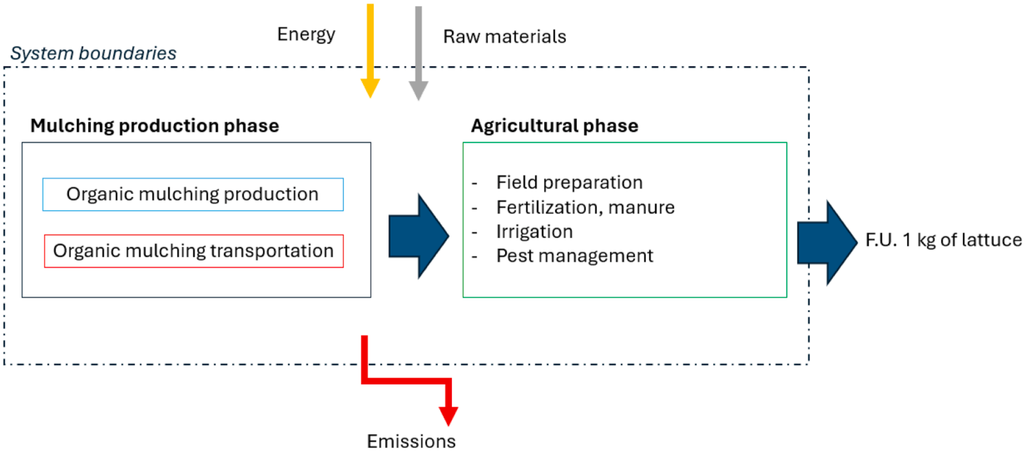

Fig. 4. System phase boundaries and functional unit(F.U), input of materials and energy and output of emission.

Table 2

Farm1 inventory for each observed experiment associated with 1 kg of fresh lettuce, the acronyms report the year, the month of the experiment, the type of mulching (OM$_{11}$ or OM$_2$) and the Control plot (C).

FARM 1	Unit		2021_AUG_C	2021_AUG_OM$_{1,1}$	2022_JUL_C	2022_JUL_M	2022_SEP_C	2022_SEP_OM$_2$
INDIRECT WF	FUEL AND ELECTRICITY							
	diesel	kJ	115	112.8	42.9	27.4	124.5	108.1
	electricity, low voltage	MJ	0.1	0.4	0.09	0.05	0.08	0.04
	FERILIZER							
	NPK 20–5–10	g	25.4	25.4	6.1	3.9	23.5	20.4
	Manure	g	29	29	16.2	10.3	117.6	102.2
	PESTICIDE							
	Cabrio duo	g	0.1	0.1				
	KERB 80	g	0.1		0.02		0.06	
	Ridomil Gold R	g	0.1	0.1	0.03	0.02	0.1	0.8
	SCHERMO 0.5 G	g	1.1	1.1				
	Signum	g	0.1	0.1				
	Switch	g			0.4	0.3	1.2	1
	MULCHING							
	transport	kg*km		21.5		0.8		3.9
	Hemp PLA felt	g				3.3		15.4
DIRECT WF	WATER USE							
	Irrigation	l	92	80.4	44.7	34.9	54.1	24.5

Table 3

Farm2 inventory for each observed experiment observed associated with1 kg of fresh lettuce. The acronyms report the year, the month of the experiment, the type of mulching (OM$_{12}$ or OM$_2$) and the Control plot (C).

FARM 2	Unit		2021_MAY_C	2021_MAY_OM$_{1,2}$	2022_JUN_C	2022_JUN_OM$_2$
INDIRECT WF	FUEL AND ELECTRICITY					
	diesel	kJ	289.9	122.3	105.6	104.7
	electricity	kJ	0.0147	0.05	0.07	0.06
	FERTILIZER					
	NPK 21–5–10	g	38.6	39.1	28.1	27.8
	Manure	g	38.6	39.1	28	27.8
	Urea	g			5.6	5.6
	PESTICIDE					
	Previcur	g	0.03	0.03	0.02	0.02
	KERB 80	g	0.1		0.06	
	Switch	g	0.02	0.02	0.01	0.01
	MULCHING					
	transport	kg*km		11.2		1.7
	Hemp PLA felt	g				6.6
DIRECT WF	WATER USE					
	Irrigation	l	40.7	35.3	140	119

mulching to the farms. In this case, it has been assumed a transport with an unspecified EURO6 lorry, since information on the vehicle is not available. The distance done by the OM in the first year is 114 km for Farm1 and 112 km for Farm2 while it is 252 km in the second year.

For the agricultural phase, primary data was collected through questionnaires and on-site surveys. Missing data were integrated using secondary data (e.g. production of inputs such as energy or fertilizers). Soil tillage was the same for all the trials, consisting of ploughing and harrowing the field before transplanting the crop. The associated fuel consumption has been estimated according to the power of the machinery used and the time length of each operation. Farm1 uses agricultural machinery with a power of 70 HP for 2 hours to prepare the soil; Farm2 uses two machines with respectively 100 and 70 HP for a time length of 90 minutes for the operations. Both farms used mixed fertilizers and manure for their soil preparation. For the 2021 trial, Farm1 used for the first trial 70 kg of mixed fertilizer (N-P2O5-K2O in this proportion 20–5–8) and 80 kg of manure. For the two trials realized in 2022, the mixed fertilizer was reduced to 30 kg and the manure increased to 160 kg. Farm 2's fertilization was for both years of 50 kg of mixed fertilizer (N-P2O5-K2O in this proportion 21–5–10) and 50 kg of manure. In the second year (i.e. 2022), 10 kg of Urea were added. Both the mixed fertilizer and the manure were modelled in OpenLCA combining existing Ecoinvent elements and reported to the selected functional unit (all the details are reported in the supplementary material). Besides the fertilizers, all the pest control were also included in the LCA model. Information regarding the characterization of fertilisers and pesticides is given in the Supplementary Material.

Irrigation volumes were measured every 10 days from the water meters installed at the head of each irrigation system realized for the different trials. Fig. 5 reports the water use for all the trials in both farms.

The electricity consumption associated with irrigation has been estimated based on the characteristics of the pumps installed in the two farms. Two pumps with 4 KW are installed in Farm1 with photovoltaic electricity used for irrigation purposes, and a single pump with 7 HP is installed in Farm2.

Wet Biomass data were retrieved at the end of each growing cycle, collecting 10 plants randomly and weighing them directly on the field.

All the elements of the LCI have been converted into water volumes according to the midpoint level characterization factors of the Recipe impact assessment methodology (Huijbregts et al., 2016). The characterization factor at midpoint level is m^3 of water consumed per m3 of water extracted, the WF results are reported differentiating between the direct component (WFdir), i.e. the water consumption for irrigation, and the indirect component (WFind), i.e. all the water needed for the production process of the farm's inputs (i.e. diesel, fertilizer, electricity). Finally, a correlation analysis between the WFtot and WFdir against the WP was done to assess how the two indexes are related. The Pearson correlation coefficient (r) and the R2 are used for this analysis.

2.2.3. *AquaCrop model*

The AquaCrop model by FAO (Vanuytrecht et al., 2014) was used to perform agro-biophysical simulations on a daily basis in Farm1, which was selected for the AquaCrop simulation due to its uniform conditions throughout the study period. AquaCrop facilitates the quantitative analysis of dynamic changes in crop biomass accumulation and yield formation by considering water use patterns (Raes et al., 2009; Steduto et al., 2012). The model is composed of four submodules: (1) the climate module, which encompasses maximum and minimum temperatures, rainfall, reference crop water demand (ET0), and CO_2 concentration; (2) the soil module, which deals with soil profile characteristics and groundwater conditions; (3) the crop module, covering crop growth, development, senescence, and production processes; (3) the management module, addressing irrigation and field management practices such as fertilization, mulching, field surface management, and weed control.

The climate module was set up through daily data obtained from a nearby weather station (San Giustino, Scandicci, 43° 75' N - 11° 19' E) of the Toscana Region weather network (https://sir.toscana.it last access: 19/02/2024). Each station measures rainfall (mm), solar radiation (Wm^{-2}), wind speed ($m\ s^{-1}$), relative humidity (%) and maximum and minimum temperature (°C). The reference evapotranspiration (ET0) was measured according to the FAO guidelines using the Penman-Monteith equation (Allen, 1998) and the observed data.

The farm soil data included in the soil module was directly retrieved from the farmer. The hydraulic properties of the soil (Table 4) were obtained by applying pedotransfer functions used in the soil-water characteristics equations. Comparisons with mean texture class values of several datasets verified the derived moisture prediction equations. A 2000 sample USDA soil texture classes were compared to estimated

Table 4
Non-conservative parameters for non-mulched and mulched lettuce crops in Farm1.

Farm	Depth (m)	Soil Texture	PWP (vol%)	FC (vol%)	SAT (vol%)	Ksat (mm day-1)
1	1.5	Silty	24	37	47.2	64.8

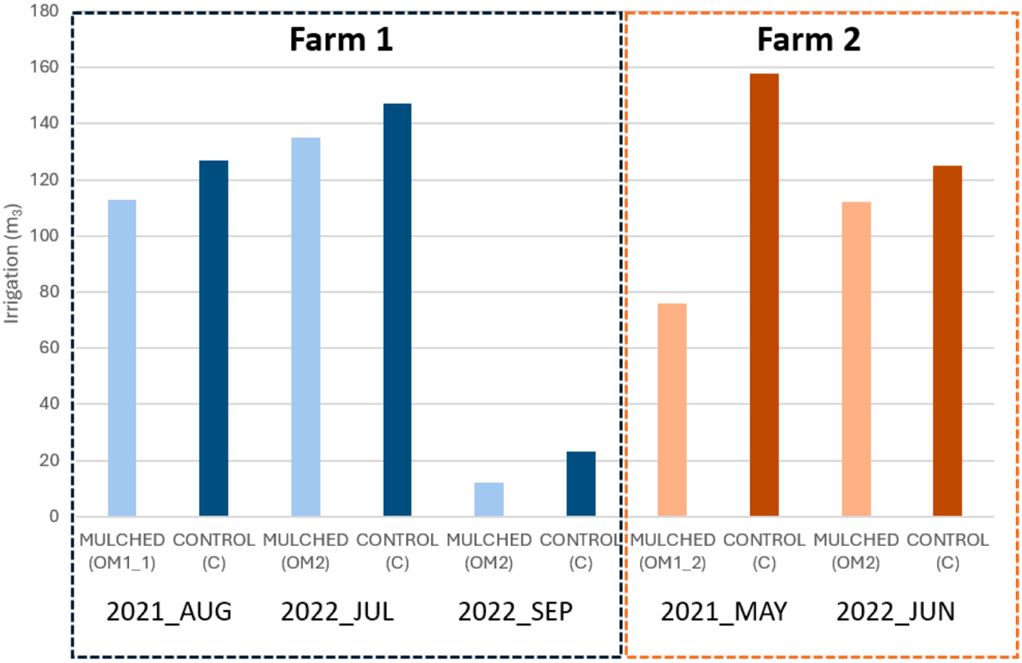

Fig. 5. Water volume consumption in the two farms for each trial. On the left, the blue bars represent the irrigation water volume for Farm1, lighter blue is with OM, darker blue is without (C). Red bars are Farm 2 irrigation volume, dark red are control experiment, (C) light red the mulched one (OM).

values by the correlation equation (Saxton andWilley, 2006).

The crop module was created integrating field measurement with literature data regarding the simulation and parametrization of lettuce in similar environments. Parameters from the literature (Amirouche et al., 2021; Ket et al., 2018; Sabzian et al., 2021) and the AquaCrop default crop file were used as references. The following parameters were deducted after direct observations on the field: number of plants per hectare, maximum root depth, plantation layout, time from transplanting to recovery, to maximum rooting depth and to maturation stages. The dry biomass production was obtained by drying in the oven and weighing the same collected sample for the WP analysis. Two different crop files were created since a difference in plant development was detected between the mulched and non-mulched thesis throughout the experiments. Table 5 represents the non-mulched and mulched treatments respectively, with the observed timing of the phenological phases to improve the simulation performance.

The management module was created by inserting the observed irrigation data from the hydrometer every decade and then averaging the value to obtain a daily volumetric irrigation amount (m^3) for both mulched and non-mulched experiments. Then, the water depth value (mm) was measured by dividing each volume by the corresponding area to insert into AquaCrop. A management module was created to simulate the mulching effect, as in AquaCrop mulching technique and type can be added, and OM was selected.

The model was calibrated targeting the dry biomass and WP for the cropping season 2021. Due to the different recovery times after the lettuce transplants, hence different growing cycle durations, two different calibration set-ups were created for the experiments with and without the mulching. The calibration process was manual, changing the non-conservative parameters that influence the crop development hence the biomass production to reach the minimum difference between simulated and observed values (Hsiao et al., 2009). The lettuce samples, which were collected, dried and weighed, were used as a reference value for comparison with the simulated lettuce dry yield. The calibration output indicates that the model slightly underestimated the yields of dry biomass per hectare of the non-mulched case, while it overestimated that obtained in the OM experiments. Indeed, the yield observed in the non-mulched and mulched trials is 2.534 t ha^{-1} and 2.584 t ha^{-1}, respectively, whereas the simulated ones are 2.448 t ha^{-1} and 2.622 ton ha^{-1}, respectively for the calibration year 2021.

After calibrating the model, new irrigation scenarios were simulated according to simulated soil moisture depletion thresholds to assess the difference between a precision irrigation schedule (i.e. 50 % depletion of readily available water was set as a starting point for irrigation events to refill up to field capacity) and the real farmer's one, made by previous growing experience and personal sensibility.

3. Results

3.1. Water productivity

The experimental trial results (Table 6) show the beneficial effect of using OM in both farms with a reduction in water consumption, thus, an increase in water productivity. When evaluating water productivity during the dry season, WPi and WP_c show similar values; however, there are notable variations between the control and mulched plots.

In Farm 1, during the first experiment (2021_AUG), the WP_i for the $OM_{1,1}$ plot was 12.45 kg m-^{3}, compared to 10.87 kg m^{-3} for the control plot. Due to the low rainfall, the difference in WP_c between both plots was minimal at only 0.30 kg m^{-3}. In the second-year experiment (2022_JUL), the newly introduced mulching film (OM_2) improved WP_i significantly, reaching 28.66 kg m^{-3} compared to 16.8 kg m^{-3} for the control, while WP_c remained nearly unchanged, with only a 0.08 kg m^{-3} difference. The second experiment of the same year (2022_SEP) showed greater variation due to higher precipitation (123 mm) during the cropping cycle. The OM_2 plot had the highest WP_i value at 40.78 kg m-^{3}, compared to 18.48 kg m-3 for the control, as it required less irrigation water. However, when considering WP_c, the value for the mulched plot was halved to 17.43 kg m^{-3}. Similarly, the control plot's WP_c dropped to 10.88 kg m^{-3}.

In Farm 2, the first experiment (2021_MAY) showed lower WP_i values overall. However, the mulched plot ($OM_{1,2}$) achieved nearly double the WP_i of the control, with 8.92 kg m-3 compared to 4.69 kg m-3. WP_c values were relatively similar, at 8.12 kg m^{-3} for $OM_{1,2}$ and 4.41 kg m^{-3} for the control. In the second year (2022_JUN), the difference in WP_i between the mulched plot (OM_2) and the control was only 0.90 kg m^{-3} (8.02 kg m^{-3} and 7.12 kg m^{-3}, respectively), with negligible differences in WP_c for both plots.

3.2. Water Footprint

The WF results of Farm1 (Fig. 6) show that the trial of July 2022 with the OM_2 has the smallest WF_{tot} (equal to 0.13 m^{3}kg^{-1}). This is mainly due to the higher plant density (17 pl m^{-2}) and plant weight (0.800 kg pl^{-1}), even if the total irrigation water is the second highest (135 m^3). WF_{ind} for electricity accounts for 0.07 m^{3}kg^{-1}, and direct blue WF is

Table 5
Non-conservative parameters for non-mulched and first experiment mulched ($OM_{1,1}$) mulched lettuce crops in Farm1.

Parameters	Reference values	Source	Farm1 non-mulched	Farm1 mulched	Units/Meaning
Maximum effective rooting depth (Observed)	0.15	Observed	[0.15]	[0.15]	m
Soil surface covered by an individual seedling	14–15; 5–6	(Amirouche et al., 2021; Ket et al., 2018)	[15]	[15]	cm^2 (At 90 % emergence)
Number of plants per hectare (Observed)	91827	Observed	[91827]	[91827]	Plants/ha
Canopy growth coefficient (CGC)	14.3–15.3; 16.8–18.5	(Amirouche et al., 2021; Ket et al., 2018)	[20.5]	[21.6]	Per day % CC increase
Maximum canopy cover (CCx)	77–81; 44–20 96.2–96.4	(Amirouche et al., 2021; Ket et al., 2018; Sabzian et al., 2021)	[90]	[90]	%
Canopy decline coefficient (CDC)	8.0	(Amirouche et al., 2021)	[14.1]	[12.7]	Per day % CC decrease
Time from transplanting to recover transplant	5	Observed	[5]	[4]	Calendar days
Time from transplanting to maximum rooting depth	25	Observed	[25]	[24]	Calendar days
Time from transplanting to maturity	40	Observed	[40]	[40]	Calendar days
Water productivity	19; 16	(Amirouche et al., 2021; Ket et al., 2018)	[15]	[15]	g/m2
Base temperature	7; 4	(Amirouche et al., 2021; Ket et al., 2018)	[5.5]	[5.5]	°C
Upper temperature	30; 28	(Amirouche et al., 2021; Ket et al., 2018)	[30]	[30]	°C

Table 6
Observed field value for lettuce in the different cropping cycles analysed.

TRIALS	Irrigation (m^3)	Precipitation (mm)	P_e (m3)	Plant irrigation volume (l)	Average weight/plant (kg)	Water consumption (l kg^{-1})	WP_i	WP_c
FARM 1								
AUG_2021_OM_{11}	113	10.4	3.49	37.7	0.47	80.4	12.45	12.08
AUG_2021_C	127	10.4	3.49	42.3	0.46	92	10.87	10.58
JUL_2022_OM_2	135	3.4	0.64	28.1	0.81	34.9	28.66	28.52
JUL_2022_C	147	3.4	0.64	30.6	0.69	44.6	16.8	16.73
SEP_2022_ OM_2	12	123.8	16.08	11	0.45	24.5	40.78	17.43
SEP_2022_C	23	123.8	16.08	21.1	0.39	54.1	18.48	10.88
FARM 2								
MAY_2021_OM_{12}	76	54.2	7.47	19.6	0.17	113	8.92	8.12
MAY_2021_C	158	54.2	9.96	23.5	0.11	213.6	4.69	4.41
JUN_2022_ OM_2	112	1.6	0.34	22.4	0.19	119.1	8.02	7.99
JUN_2022_C	125	1.6	0.34	25	0.18	140.4	7.12	7.1

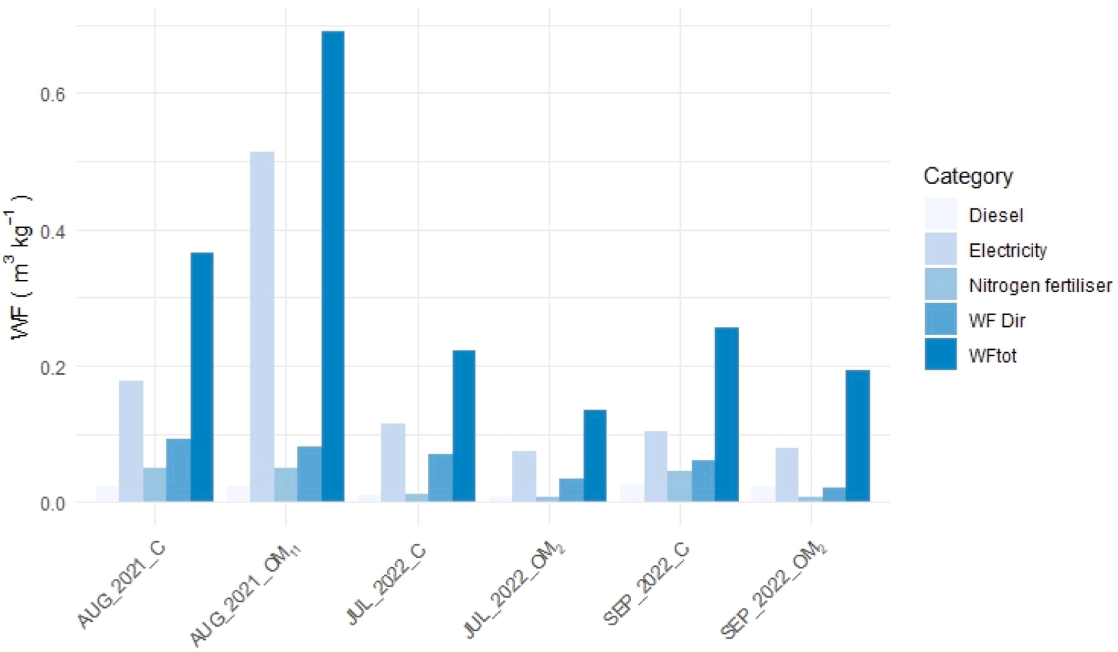

Fig. 6. WF chart of Farm1 for all the experiments. The letter after the month means mulching with biodegradable felt for "OM_{1_1}", "OM_2" for PLA fiber mulching and non-mulched for "C". The dark blue bar shows the WF_{tot}, of each trial. The main components contributing to the WF_{tot}, are reported. 1 % cut-off criteria were applied to avoid reporting categories of little significance. All the values are reported as m^3kg^{-1}.

0.03 m^3kg^{-1}. However, WF_{tot} is 0.22 m^3kg^{-1} in 2022_JUL_C where electricity WF and WF_{dir} contribute 0.11 m^3kg^{-1} and 0.07 m^3kg^{-1}.

The highest WF_{tot} is observed during August 2022 with OM_{1_1} (equal to 0.68 m^3kg^{-1}). The most contributing component is in this case electricity, 0.51 m^3kg^{-1} associated to the production of the OM_{1_1} that has is not reusable, thus determining an higher impact for the single trial.

In case of Farm2 (Fig. 7), the trial of May 2021 with OM_{1_2} shows the highest WF_{tot}, i.e. 0.46 m^3kg^{-1}. In this case, direct water use plays a major role due to a large amount of irrigation, 158 m^3, WF_{dir} was 0.11 m^3kg^{-1}. Moreover, the electricity for the OM_{1_2} production contributes with 0.18 m^3 kg^{-1}.

The non-mulched trial of May 2021 has a slightly lower WF, 0.43 m^3kg^{-1}. Indeed, the higher WF due to the irrigation (0.21 m^3kg^{-1}) is compensated reduced impact of electricity impact due to the electricity.

Looking at June 2022 trials the overall WF_{tot} is quite similar: 0.28 m^3 kg^{-1} for both the mulched and non-mulched trials.

Table 7 reports the summary of the results of the different indicators measured in the research for all the experimental plots. The linear regression (Fig. 8) of both WP_i and WP_c vs WF_{tot} and WFdir are reported. The coefficient of determination (R2) resulted in 0.684 for WP_i vs WF_{dir} and 0.332 for WP_i vs WF tot. Thus, WP_i is quite a good predictor, and it relatively matches the variation of WF_{dir}, Moreover, the Pearson correlation index (r) results report a solidly negative correlation for WFdir, r (8) −.82, p = .01 highlighting a connection between the two indicators, been one the inverse of the other.

Contrarily, within the other indicators we observe a low value of relationships but also of prediction, a moderate negative correlation for WF_{tot} r (8) −.57, p = .01 was measured. Finally, looking at WP_c vs WF the value of the coefficient of determination falls to 0.072 and there is almost no correlation if we measured the Pearson index r (8) -. 26. Although a weak negative correlation is observed between WF_{dir} and WP_c, with r (8) −.62 the R^2 measured(0.387) states that the variation in WF_{dir} is not well explained by WP_c

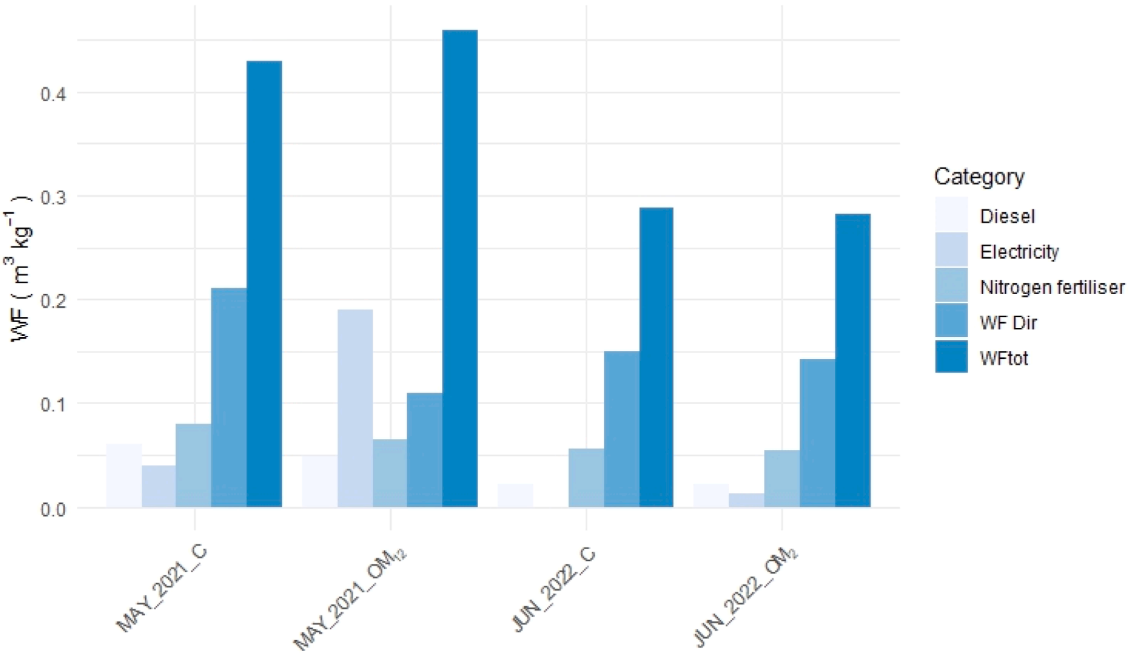

Fig. 7. WF chart of Farm2 for all the experiments. The letter after the month means mulching with recycled felt for "OM_{1_2}", "OM_2" for PLA fiber mulching and non-mulched for "C". The dark blue bar shows the WF_{tot}, of each trial. The main components that contribute to the WF_{tot}, are reported. 1 % cut-off criteria were applied to avoid reporting categories of little significance. All the values are reported as m^3kg^{-1}.

Table 7
summary of the $WP_{i,}$ WP_c,WF and WF_{dir} for all farms' experiment.

	FARM 1						FARM 2			
	2021_AUG		2022_JUL		2022_SEP		2021_MAY		2022_JUN	
	(OM_{1_1})	(C)	(OM_2)	(C)	(OM_2)	(C)	(OM_{1_2})	(C)	(OM_2)	(C)
WP_i	12.45	10.87	28.66	16.80	40.78	18.48	8.92	4.69	8.02	7.12
WP_c	12.08	10.58	28.52	16.73	17.43	10.88	8.12	4.41	7.99	7.10
WF	0.69	0.13	0.19	0.36	0.20	0.25	0.46	0.28	0.43	0.29
WFdir	0.08	0.03	0.02	0.09	0.04	0.05	0.11	0.12	0.21	0.14

3.3. *Aqua crop scenario analysis*

AquaCrop simulations (Table 8) show a high reduction in the irrigation water requirements for lettuce compared to the volumes measured in the field. A reduction of 86 % and 95 % of water consumption is observed both in the non-mulched and mulched (OM_{1_1}) settings.

The WP and WF are very sensitive to the reduction of irrigation volume simulated. The WP in the mulched case rises to 291.6 kg m^{-3} due to the low irrigation volume (150 m3) meanwhile it increases to 83. 3 kg m^{-3} in the non-mulched experiment.

On the other hand, WF is reduced both in mulched (0.46 m3 kg-1) and non-mulched (0.13 m3 kg^{-1}) cases although the use of OM1_1 still determines a higher value of WF compared to non-mulched case due to the impact associated with the electricity consumption needed to produce the mulching.

4. Discussion

In this study, water footprint and water productivity are combined to provide a comprehensive assessment of the effects of organic mulching on water resources. The WP results obtained (with an increase between 5 % and 50 %) are in line with existing literature (Li et al., 2021, Michelon et al., 2020) confirming the positive effects of mulching on water productivity. This is due to the combination of irrigation volume reduction and plant biomass increase. The latter appears to be influenced also by the plant density, with the lowest lettuce yield observed when high plant densities are adopted (Beccafichi et al., 2005). However, the plant weight is aligned with data retrieved in literature for similar study areas with an average biomass between 0.46 and 0.86 kg plant m^{-2} (Di Mola et al., 2022). OM has shown good performance in reducing water irrigation amount in each experiment, with reductions ranging between 8 % and 50 %. Similarly, Biswas et al. (2016) found a reduction of 50 % of the irrigation water in tomato cultivation, while El-Metwally et al. (2022) found a reduction of around 20 % for potatoes. However, the growing period has a major role in determining water irrigation requirements and OM efficacy, as confirmed by the trial of September 2022 (Farm1) and May 2021 (Farm2). In particular, the trial of September 2022 (SEP_2022_ OM_2) resulted in a WP drop to 17.43 kg m^{-3} considering the effect of $P_{e.}$ Hence, precipitation plays a major role in satisfying the lettuce water requirement, where the OM performance can be more related to maintaining humidity in the root zone, reducing soil water evaporation.

The WF analysis allows to enlarge the assessment including the water-related impacts of OM production as well as those associated to the agricultural phase (besides irrigation). Focusing on WF_{dir}, the analysis reveals the beneficial effect on water resources of OM with OM_2 scoring better performances compared to OM_{1_1} and OM_{1_2}. however, only the 2022_ JUL_OM_2 experiment in Farm 1 shows a WF_{dir} below the average value of lettuce WF (Le Roux et al., 2016; Mekonnen and

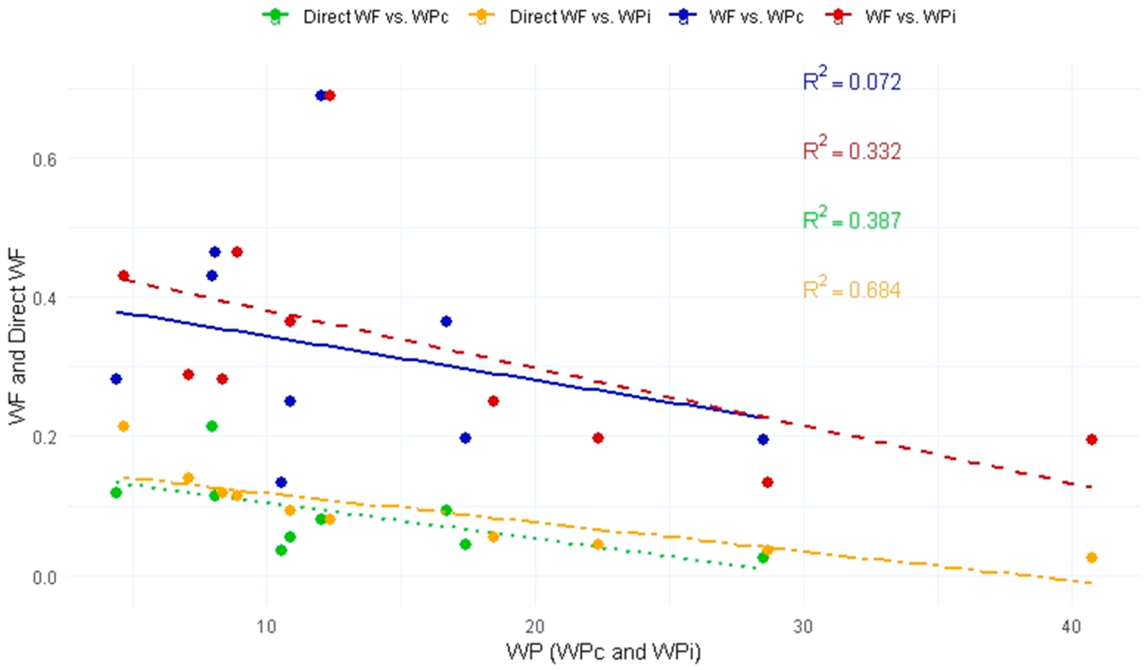

Fig. 8. Correlation analysis for the lettuce:WF_{dir} vs WP_c (green), WF_{dir} vs WP_i (yellow), WF vs WP_c (blue) and WF vs WP_i (red) in the chart are reported the R^2 value colored as the correspondent trend lines.

Table 8
AquaCrop simulation results for the August Farm1's trail with mulched and control treatment using traditional (Ti) and precision (Pi) irrigation schemes. Water Footprint (WF) and Water Productivity (WP) are measured according to the new amount of irrigation water volume.

	Biomass (kg ha^{-1})		Irrigation (m^3ha^{-1})		Drainage (mm)		Evapotranspiration (m^3)		Wpi (Kg m^{-3})		WF(m^3kg^{-1})	
	Oi	Pi	Oi	Pi	Oi	Pi	Oi	Pi	Oi	Pi	Oi	Pi
Control	40800	40817	3550	490	302	5	371	365	11.5	83.3	0.36	0.13
Mulched	43700	43733	3040	150	294	7	357	356	14.4	291.6	0.68	0.46

Hoekstra, 2011; Mialyk et al., 2024), mainly due to high crop production. Farm 2, always shows worse values of WF compared to the literature, disclosing a potential waste of irrigation during the experimentation. Investigating the entire WF, the analysis shows the role played by the type of mulching adopted revealing the hidden impacts of the different OM types. This is an interesting case of water-energy nexus (Pacetti et al., 2015), with the WF associated with the electricity needed for the OM_{1_1} production having the highest share of impact among all the WF categories (0.36 m^3 kg-1) and determining the highest overall WF of all trials. The explanation is twofold: on one hand, the higher weight of the OM_{1_1} (800 g m^{-2}); on the other hand, the scarce resistance of the felt that allows the use of this OM type only for one crop cycle, rather than being reusable for a longer period. Indeed, WF allows a better understanding of the sustainability of introducing OM, highlighting the potential benefits of OM as already shown by other studies (e.g. Wang et al., 2022; Chukalla et al., 2015), but also stressing the necessity of adopting a production chain perspective to avoid hidden impacts that can invalidate the direct benefits obtained. Furthermore, an important aspect to be further explored when dealing with WF in LCA remains the choice of the impact assessment methodology and the use of different characterization factors. Indeed, LCA relies on various approaches to quantify environmental impacts, including those related to water use. However, these methodologies often differ in their approach to assessing water impacts, leading to potential variability in results (Fang and Heijungs, 2015)

The correlation analysis demonstrates that WP and WF are reciprocal (as in Amarasinghe and Smakhtin, V., 2014) only looking at direct WF (irrigation) while their correlation became weaker if the entire WF is taken into account, highlighting the need for multiple water use indicators. While WP_i captures the effect of mulching film on increasing the productivity of irrigation water, WP_c provides insight into the impact of climate on crop productivity by showing the contribution of precipitation. Thus, WP_i closely reflects WFdir, but when considering the total WF, the latter offers a broader understanding of water use. When combined with WP_c, the role of green water (precipitation) can be accounted for in the evaluation, something that the WF-LCA does not consider. AquaCrop simulations completed the assessment demonstrating the mismatch between the crop water requirements and the observed agricultural practice. Indeed, the simulations reveal a considerable irrigation surplus (between 86 % and 95 %) regardless of the use of mulching. The amount of irrigation estimated with the model is consistent with previous studies in nearby areas (Bonanomi et al., 2017) reflecting an overestimation of farmer irrigation schemes. This excess in irrigation can be explained by the necessity of maintaining high soil moisture to meet the leaf quality parameters for lettuce commercialization (REGIONE CAMPANIA, 2024). Moreover, the excess of irrigation can't be only considered as a loss due to return flow that can contribute to local water bodies recharge or nitrate dilution (Rotiroti et al., 2019). However, the comparison between the simulation and the observation highlights the necessity of revising the agricultural water management strategy on the farms. Finally, co-designing the experiment with farmers introduced some limitations, as it required balancing production needs with the scientific rigor of the experimental design. Nevertheless, the direct involvement of farmers can accelerate technology transfer and enhance innovation readiness (Pawera et al.,2024)

5. Conclusion

Water use indicators and crop models are useful tools to support farmers in making informed decisions regarding the performance of their irrigation management and water savings practice. To meet the new challenge of managing diminishing natural resources, it is essential to raise awareness of water-saving strategies among farmers. This is especially important in regions where water availability and cost have traditionally not been limiting factors This study has shown how OM felts usually have a positive effect on lettuce production, both in terms of WP and WF. However, the WF results allowed to show how the felt type can jeopardize the water savings determined by the reduction of irrigation due to the WF associated with the felt production. The combination of WF and WP indicators, together with the possibilities of exploring alternative agricultural management strategies through modelling, can be a valid approach for the farmers to obtain a complete information on the environmental impact of their production and the efficiency of farm management. This study reinforces OM's role in water productivity improvements but also stresses the importance of considering lifecycle impacts and refining water management practices to maximize sustainability in agriculture. The findings have significant managerial and policy implications, as they highlight the need for policymakers to promote sustainable water management strategies, such as the adoption of organic mulching, while encouraging farmers to optimize irrigation practices and consider the full lifecycle impacts of agricultural inputs to reduce hidden environmental costs.

CRediT authorship contribution statement

Pacetti Tommaso: Writing – review & editing, Methodology, Formal analysis, Data curation, Conceptualization. **Renzi Niccolò:** Writing – review & editing, Writing – original draft, Visualization, Data curation, Conceptualization. **Castelli Giulio:** Writing – review & editing, Visualization, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lompi Marco:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Setti Andrea:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Bresci Elena:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization. **Caporali Enrica:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Spinelli Daniele:** Data curation, Funding acquisition, Investigation, Resources, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Erica Caporali reports financial support was provided by Tuscany Region. Giulio Castelli reports financial support was provided by Ministry of Education and Merit. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2025.109380.

Data availability

Data will be made available on request.

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