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# Cropping systems and agricultural management strategies affect soil organic carbon dynamics in semi-arid regions

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**Introduction:** Soil organic carbon (SOC) dynamic is one of the important factors that directly influence soil properties and quality. In agro-ecosystems, the SOC dynamics are strongly linked to agricultural management practices.

**Methods:** In this study, we investigated the response of SOC and its fractions to various combination of agricultural management practices based on measurements obtained from an experiment conducted over four growing seasons from 2018 to 2020 in Ahvaz, Iran. The experimental treatments involved three agricultural strategies combined with four crop rotation systems. The agricultural strategies comprised conventional (CON: mineral fertilizer, removal of all crop residues), organic (ORG: organic fertilizer, 30% return of crop residues to the soil), and integrated (INT: mineral/organic fertilizer, 15% return of crop residues) strategies. The crop rotation systems were: fallow-wheat (F-W), corn-wheat (C-W), sesame-wheat (S-W), and mung bean-wheat (B-W). Soil samples were collected from all treatments and SOC, labile-C, and non-labile-C were measured.

**Results and discussion:** After two years of experiment, no significant improvement was found in SOC of CON strategy ( $p \leq 0.05$ ). The ORG and INT strategies contained on average 1.1 and 1.06 times more SOC than the CON strategy, respectively. The value of labile-C was decreased during summer cultivations and increased in the soil samples collected after winter cultivations. However, although the quantity of labile-C in ORG ( $2 \text{ g kg}^{-1}$ ) was higher than INT ( $1.83 \text{ g kg}^{-1}$ ) and CON ( $1.87 \text{ g kg}^{-1}$ ) overall during the experiment time, after the second summer cultivation despite the gradual accumulation of organic matter due to high levels of temperature and humidity, the content in ORG reduced to  $1.47 \text{ g kg}^{-1}$ . In all three agricultural management strategies, the SOC content in the four rotation systems was according to the following descending order B-W ( $5.7 \text{ g kg}^{-1}$ ) > C-W ( $5.29 \text{ g kg}^{-1}$ ) > S-W ( $5.23 \text{ g kg}^{-1}$ ) > F-W ( $4.52 \text{ g kg}^{-1}$ ). Therefore, for this region M-W and S-W crop rotation systems are recommended in addition to C-W (which is the most common rotation system). However, crop rotation systems were more beneficial for C-sequestration when combined with organic and inorganic fertilization and crop residue incorporation.

This study gives promising results for implementing INT and ORG strategies under long-term cropping systems containing various summer crops in rotation with wheat for improving SOC dynamics in semi-arid regions in Iran.

#### KEYWORDS

carbon sequestration, crop rotation, crop residue, labile-C, weather variation

## 1. Introduction

Agroecosystems are the largest carbon (C) pools in terrestrial ecosystems, with global storage of over 1,550 GT (Batjes, 1996). In fact, cropland soils alone account for 590–1,180 million tons of C that are stored as soil organic matter originating from crop residues and manure (FAO., 2002). SOC sequestration has been recognized as one of the main agents in improving ecosystem services including soil quality upgrades by improving soil organic matter and total nitrogen (Khormali et al., 2009), retention of water and nutrients (Tisdall and Oades, 1982), increasing agricultural productivity (Plaza-Bonilla et al., 2016), improving soil aggregate stability and soil structure (Ayoubi et al., 2012; Zeraatpisheh et al., 2021), control of erosion (Rahimi et al., 2013; Li et al., 2016), and enhancing surface and subsurface water quality (Laird, 2008). Sequestration of C in soils is also a natural process to mitigation of global warming through reduction in atmospheric CO<sub>2</sub> levels (Afshar et al., 2010; Brandão et al., 2013). Soil C pools, which are an important energy source for the soil food web (Chan et al., 2001) and improving nutrient cycling, are primarily the labile organic carbon pools (Luo et al., 2019). They comprise fractions of SOC pools with most rapid turnover times from days to months (Li et al., 2018). These fractions affect soil formation and its functions in multiple ways and are recognized as indicators for representing soil quality (Benbi et al., 2015). Potassium permanganate oxidizable organic C (KMnO<sub>4</sub>-C, here after labile-C) is one of the labile-C fractions which is estimated by the chemical oxidation method using KMnO<sub>4</sub> (Blair et al., 1995). It has been suggested as the most sensitive indicator to investigate the effect of agricultural management strategies e.g., organic and inorganic fertilizer application, returning crop residues to the soil, crop rotation systems, and tillage regimes on dynamics of soil organic labile-C (Plaza-Bonilla et al., 2014; Blanco-Moure et al., 2016). The non-labile-C fraction, which has remarkably low degrees of stabilization decomposition over time, and had high recalcitrant to conversion in response to agricultural practices

can be calculated based on the difference between SOC and labile-C (Majumder et al., 2008).

Many agricultural practices have been adopted as restorative management strategies to improve soil fertility by storing more C in soils. These include: green manure incorporation into the soil (Maltas et al., 2018), reduced tillage (Calegari et al., 2008), crop rotation (Gregorich et al., 2001), crop residues managements (Chalise et al., 2018; Stella et al., 2019; Radicetti et al., 2020), and nutrient management (Havlin, 2020), all which influence the amount of C retained in the soil. For instance, integrating organic manure with mineral fertilizers (Diekow et al., 2005; Liu et al., 2014; Maltas et al., 2018), returning crop residues to the soil instead of removing them (Liu et al., 2013), improvement in root and shoot biomass as a result of using mineral fertilizers (Cambardella and Elliott, 1992; Bhattacharyya et al., 2012) are among practices that have been introduced to improve the amount of SOC and labile-C levels. The technical potential of these management practices on SOC improvement varies in the range of 100–1,000 kgC ha<sup>-1</sup> year<sup>-1</sup> based on the soil properties and climate conditions across different regions globally (Lal, 2010). Moreover, along with organic and inorganic resources management, appropriate rotation of crops is an important factor in SOC dynamics. For example, the inclusion of legumes in different crop rotation systems considerably promoted SOC pools compared to cereal-cereal cropping system and sole cereal cropping (Liu et al., 2020).

Despite the abundance of reseaches revealing the positive effects of different combinations of crop rotation and agricultural strategies on C-sequestration (Diekow et al., 2005; Ding et al., 2012; Yadav et al., 2019), so far few studies have explored the variations of SOC and labile-C dynamics in semi-arid regions (Maia et al., 2007) comprising summer crops cultivation in rotation with winter crops (like wheat) i.e., two growing seasons in 1 year. Understanding these dynamics under such particular cropping systems is crucial for two reasons. First, since the weather during two growing seasons of these regions vary between dry in summer and wet in winter periods, it is still not clear if the dynamics remain similar under both conditions. Second, considering the fact that arable lands in semi-arid regions have small SOC pools, it is vital to optimize fertilization, crop rotation systems, and crop residues management in order to alleviate the environmental impacts and ameliorate SOC pools (Samal et al., 2017; Chen et al., 2018; Li et al., 2018).

Abbreviations: CON, conventional agricultural strategy; ORG, organic agricultural strategy; INT, integrated agricultural strategy; C, carbon; SOC, soil organic carbon, F-W, rotation of fallow-wheat; C-W, rotation of corn-wheat; S-W, rotation of sesame-wheat; B-W, rotation of mung bean-wheat.

With this study, we aim to contribute to the literature on this topic by investigating the role of various crops planted in rotation with wheat in combination with residue management and organic fertilizer application in semi-arid regions. Khuzestan province, located in the southwestern part of Iran, has been selected as a case study in semi-arid area. The region is the main center to produce high quality and quantity grain wheat with the 1.37 million Mg ha<sup>-1</sup> year<sup>-1</sup> productivity (*Iran Wheat Flour Exported to Oman, Italy, Iraq, 2021*) in the country. Continuous monocropping and wheat-maize cultivation as two conventional cropping systems (*Hajabbasi and Hemmat, 2000; Kabiri et al., 2015*) together with high temperature (*Cooper et al., 2011*) in the most parts of Khuzestan province have led to depletion of soil organic carbon (SOC) stocks. In addition, the values of SOC in semi-arid regions are fundamentally low owing to high levels of oxidation (*Maia et al., 2019*). Due to intensive farming, about 50%–67% of the original SOC pools in cultivated soils can be lost in semi-arid regions (cumulative amount about 30–40 t C ha<sup>-1</sup>) (*Lal, 2018*). Continuation of these practices will probably result in further degradation of soil quality and fertility through reducing C pools (*Yu et al., 2006*) which directly led to a decline in crop productivity (*Chauhan et al., 2012*). Therefore, in this study, we look at the contribution of various agricultural practices for SOC sequestration.

More specifically, the objectives of this study are to: (i) determine the changes in lability of C in summer crop cultivation (under high temperatures) and winter wheat crop (under wet conditions), (ii) find out the response of SOC dynamics and its fractions to various strategies of organic/inorganic fertilizers application and crop residues management in semi-arid regions, and (iii) assess and explain the effect of combinations of various fertilizing/residue management strategies with different crop rotation systems on the dynamics of SOC and its fractions.

## 2. Materials and methods

### 2.1. Study area

Khuzestan province (48°41E and 31°20N, altitude: 22.5 m), located in the southwestern part of Iran (*Figure 1A*), is one of several regions in the country known as a capital of wheat production (1.7 million Mg year<sup>-1</sup>). The average temperature in the region is 25°C with a maximum and minimum temperature of 48 and 4°C in summer and winter, respectively. The average annual precipitation is 213 mm yr<sup>-1</sup> with the highest intensity in January (*IRIMO, 2020; Figure 1B*). The dominant soil texture in the topsoil in this experimental site was sandy-loam with 67% sand, 21% silt, 12% clay (*FAO, 2021*), 0.039% total nitrogen, and total 0.45% C. Additional soil characteristics include 26 kg ha<sup>-1</sup> total phosphorus (organic and inorganic forms, *Self-Davis et al.,*

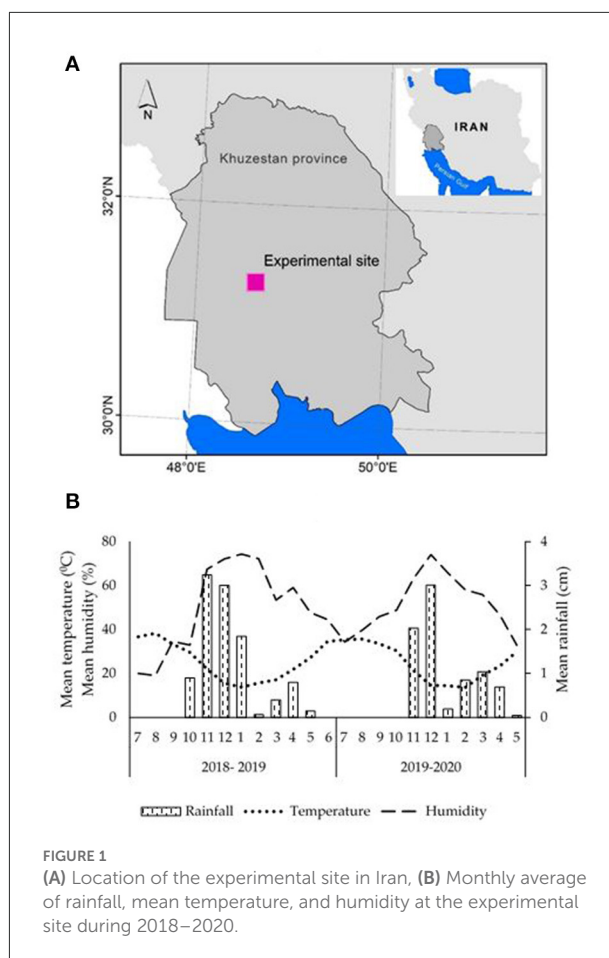


FIGURE 1 (A) Location of the experimental site in Iran, (B) Monthly average of rainfall, mean temperature, and humidity at the experimental site during 2018–2020.

2000) and 318 kg ha<sup>-1</sup> available potassium content (*Dandwate, 2020*). Saturated soil suspension with a ratio of 1 unit of soil: 2 units of water had an electrical conductivity of 3.4 dS m<sup>-1</sup> and pH of 7.8. According to the USDA, the soil of the experimental field was classified as aridisol (*Baillie, 2006*).

The total agricultural lands in the province are comprised of 700,000 ha irrigated and 500,000 ha rainfed arable. The staple crops cultivated in Khuzestan province are wheat, sugarcane, corn, alfalfa, and rice. The province is known for a good quality of wheat that contains 12%–13% protein and 28%–30% wet gluten (*Iran Wheat Flour Exported to Oman, Italy, Iraq, 2021*). The dominant cropping system in most regions is a conventionally grown double-cropping rotation of winter wheat together with summer maize/rice. However, some regions grow winter wheat as monocropping.

Khuzestan province is an emitter of CO<sub>2</sub> emissions due to the presence of oil and gas industry. About 1,529.4 Mg day<sup>-1</sup> of CO<sub>2</sub> is emitted in the region, which is 34% of the total national CO<sub>2</sub> emission (*Kamali et al., 2009; CO<sub>2</sub> Country Profile, 2021*). Although increased CO<sub>2</sub> levels are beneficial for crops in terms of the raw material required for photosynthesis,

the benefit remains only as long as increasing temperatures do not reduce the growth period of the plant. Therefore, agricultural management practices (e.g., crop rotation systems, methods of fertilization, crop residue management, and tillage types) are crucial for mitigating the amount of produced CO<sub>2</sub>.

## 2.2. Experimental design

A two-factorial randomized complete block design with a plot size of 12 m<sup>2</sup> (3 × 4 m; Hoshmand, 2018) was applied. Treatments were comprised of three different fertilizer and crop residue management strategies as: conventional (CON), organic (ORG), and integrated management strategy (INT) which are combined with four types of crop rotation system (Supplementary Figure S1). In total, 12 treatments were applied. To reduce experimental error, each factor combination was replicated three times.

The three distinct fertilizer and crop residue management (agricultural strategies) for the experimental plots were:

1. Conventional (CON): All fertilizer inputs used for all crops were chemical. The amount of nitrogen, phosphorus, and potassium applied for different crops was: 110, 100, and 100 kg ha<sup>-1</sup> for wheat; 200, 100, and 100 kg ha<sup>-1</sup>, for corn; 75, 50, and 50 kg ha<sup>-1</sup> for sesame; and 30, 50, and 50 kg ha<sup>-1</sup> for mung bean, respectively. The seeds were sprayed with fungicide (difenoconazole), which is common practice in the region. Weed invasion (the dominant weed was *Cynodon dactylon* L.) was controlled with Roundup (41% active substance glyphosate) herbicide. Crop residues were completely removed from the soil.
2. Organic (ORG): All inputs were organic and biological. No chemical fertilizer was used. The total amounts of applied compost and vermicompost (Table 1) were 15 and 10 t ha<sup>-1</sup> of fresh matter, respectively, for wheat, mung bean, and sesame and 20 and 10 t ha<sup>-1</sup> of fresh matter, respectively, for corn. Table 1 presents the detailed chemical properties of the two types of manure used. For all ORG treatment plots, a combination of two-thirds compost and one-third vermicompost was applied. Before planting the crops, the manure was evenly spread on the surface of the experimental plots and then mixed with the soil. Wheat seeds were soaked in biological phosphate fertilizer (*Pseudomonas putida* and *Pantoea agglomerans*: 10<sup>7</sup> bacteria gr<sup>-1</sup>) 1 h before planting. Weed control was conducted manually by mechanical means. In addition, 30% of crop residues (Table 1) from the preceding year were returned to the soil, which was equivalent to 90, 288, 393, and 129 g m<sup>-2</sup> for wheat, mung bean, sesame, and corn, respectively. Humic acid was sprayed at the wheat pollination stage at 5 ml L<sup>-1</sup> m<sup>-2</sup>.
3. Integrated management strategy (INT): A combination of chemical, organic, and biological fertilizers was used. The

amounts of compost and vermicompost (the same organic fertilizers that were used in ORG) were 7.5 and 5 t ha<sup>-1</sup>, respectively, for wheat, mung bean, and sesame, and 10 and 5 t ha<sup>-1</sup>, respectively, for corn. As in ORG, a combination of two-thirds compost and one-third vermicompost was used for all INT plots. In addition, we applied 50% of the total amount of fertilizers used in CON. Weed was controlled using a combination of chemical (Roundup herbicide with a concentration equal to half of that used in CON) and mechanical methods. Furthermore, only 15% of the crop residues from the preceding year were returned to the soil, which was equivalent to 45, 144, 196.5, and 64.5 g m<sup>-2</sup> for wheat, mung bean, sesame, and corn, respectively. Seeds were soaked in biological phosphate fertilizer (3R-BioPhosphate with 35% of P), and humic acid containing 6.5% of nitrogen was sprayed per m<sup>-2</sup> at half the amount of that of ORG.

The effects of natural fallow, cereal, oil seed, and legume crops as summer crops in rotation with wheat cultivation as winter crop were tested. Accordingly, we designed four crop rotation systems: (1) fallow–wheat (F-W); (2) corn–wheat (C-W); (3) sesame–wheat (S-W); and (4) mung bean–wheat (B-W; Supplementary Figure S1). The experiment began in July 2018 and ended in May 2020 (Supplementary Figure S1). The last crop cultivated on the field before the start of experiment was winter wheat under a combination of chemical and organic fertilizer applications.

The cultivation method for summer crops was furrow planting. After harvesting the summer crops, the furrows were destroyed and the soil in each experimental plot was mixed. The wheat crop was then planted in rows with inter- and intra-row distances of 7 and 2 cm, respectively (Table 2). Table 2 presents detailed information regarding the cultivar, plant density, inter- and intra-row distance, planting and harvest dates of different crops used in the experiment, and the date of soil sampling. Furrows were initially prepared using a moldboard plow. Subsequently, to prevent mixing of the experimental plots, shovels and rakes were used to prepare furrows for the summer crops and rows for the planting of wheat. Irrigation was applied on the basis of water requirements and soil moisture conditions. The water requirement for each plant was calculated using CROPWAT version 8.0 on the basis of the crop coefficient and evapotranspiration (Steduto et al., 2012). Accordingly, the irrigation requirements for one growth period were 369, 347, 337, and 315 mm for wheat, corn, mung bean, and sesame, respectively.

## 2.3. Soil sampling and analyses

After harvesting each crop, soil samples were obtained from the top 20 cm (Amini and Asoodar, 2015; He et al., 2020) of the soil (Table 2). Soil sampling was performed at three locations of

TABLE 1 Content of carbon, nitrogen, C/N, potassium, phosphorus, pH, EC, and moisture for compost and vermicompost used in the experiment.

Manure	Carbon (%)	Nitrogen (%)	C/N	Potassium (%)	Phosphorus (%)	pH	EC (dS/m)	Moisture (%)
Compost	58	1.84	31.5	0.48	0.31	7.35	3.1	15
Vermicompost	65	2.18	29.8	0.5	0.61	6.98	5.38	10
Crop residues								
Wheat	48.5	0.684	70.9	–	–	–	–	0
Corn	49.5	0.663	74.6	–	–	–	–	2
Sesame	47.5	2.8	16.96	–	–	–	–	5
Mung bean	48.5	3.3	14.7	–	–	–	–	5

TABLE 2 Cultivar, plant density, inter- and intra-row distance, planting, harvesting, and soil sampling dates (2018–2020) for different winter and summer crops used in the experiment.

Plant	Cultivar	Plant density (plant m <sup>-2</sup> )	Inter- and intra-row distance (cm)	Planting date	Harvest date	Soil sampling date
Wheat	Chamran2	400	7 and 2	10 December	26 May	28 May
Mung bean	CN-9-3	40	60 and 10	5 July	mid-October	17 October
Sesame	Darab 14	20	60 and 15	5 July	mid-October	17 October
Corn	S.C.704	8	75 and 18	10 July	mid-November	12 November

each experimental plot using an auger. The collected samples were then mixed to obtain one sample. To estimate the total SOC and the fractions of labile-C and non-labile-C, the soil samples were first air-dried and then passed through a sieve with a mesh size of 2 mm. After sieving, the substrate exhibited a uniform composition of soil aggregates <2 mm. The amount of SOC was determined using a vitriol acid-potassium dichromate wet oxidation method (Walkley and Black, 1934) and on the basis of the proposed formula by Gelman et al. (2012). For each soil sample, the amount of SOC was measured three times and the average was used as the representative value.

Labile-C was measured using the method suggested by Blair et al. (1995) in which soil samples are exposed to oxidation with potassium permanganate (KMnO<sub>4</sub>) to oxidize a proportion of total C sensitive to reaction. The absorbance of the filtered samples was read using a spectrophotometer at 550 nm. The labile-C was finally calculated according to Weil et al. (2003) as:

$$\text{Labile-C [g kg}^{-1}\text{]} = \left( \left[ 0.02 \frac{\text{mol}}{\text{L}} - (a + b \times \text{Abs}) \right] \times \left[ 9000 \frac{\text{mg C}}{\text{mol}} \right] \times \left[ 0.02 \frac{\text{L solution}}{\text{Wt}} \right] \right) \times 10000 \times 10 \quad (1)$$

where *a*, *b*, *Wt*, and *L* are the intercept of the standard curve, slope of the standard curve, weight of air-dried soil sample in kg, and volume of the stock solution reacted, respectively. The initial solution (KMnO<sub>4</sub>) concentration is 0.02 mol L<sup>-1</sup>. Abs is absorbance (at 550 nm) of filtered samples and 9,000 = mg of C oxidized by 1 mole of MnO<sub>4</sub> changing from Mn<sup>7+</sup> to Mn<sup>2+</sup>.

Accordingly, we estimated non-labile-C [%] as the difference between SOC and labile-C (Blair et al., 1995).

The following formula was used to calculate the annual change in SOC sequestration:

$$\begin{aligned} \text{SOC sequestration (t C ha}^{-1} \text{ year}^{-1}\text{)} \\ = \left[ \frac{\left( \left[ (\% \text{ SOC final} - \% \text{ SOC initial}) \times \left[ \text{BD} \frac{\text{kg}}{\text{m}^3} \right] \times [\text{Sd m}] \right] \right)}{24 \text{ months}} \right] \\ \times 12 \text{ months} \times \left[ 10 \frac{\text{t}}{\text{ha}} \right] \end{aligned}$$

where BD is the value of soil bulk density in kg m<sup>-3</sup>. Sd has intercepted soil sampling depth in meters. Twenty-four months represents the entire experiment period.

## 2.4. Statistical analyses

The effects of crop rotation systems, agricultural strategies, and their interactions on SOC, labile-C, and non-labile-C changes were tested. The analysis of variance (ANOVA) was done using the mixed method of SAS, version 9.4 (SAS Institute, 2015), based on the mixed split-plot design and considering the random effect of seasonal weather variation (summer and winter). To compare and explain the results, the means of double and triple interactions of the experimental factors were considered. Statistical results of mean comparisons were

obtained by Duncan method at a 0.05 significant probability level through SAS, version 9.4 (*p*) (Onofri, 2007).

### 3. Results

#### 3.1. Effect of agricultural strategy on the SOC fractions

The results of ANOVA revealed a significant effect of seasonal weather variation, agricultural strategy, and crop rotation system and also the interactions of these factors on SOC, labile-C, and non-labile-C at the level of  $p \leq 0.01$  and  $p \leq 0.05$  (Table 3). Our results demonstrate that the value of labile-C was notably decreased in summer both in 2018 and 2019 and increased during winter of 2019 and 2020. In most cases, ORG and INT (compared with CON) had a considerable positive effect on improving the labile-C amount over time with the exception of summer 2019, in which the ORG samples exhibited significantly lower labile-C than those in INT and CON (Figure 2B). The highest value of SOC ( $5.6 \text{ g kg}^{-1}$ ) was observed in ORG after winter 2020 (Figure 2B). Unlike for the INT and ORG agricultural strategies, the content of SOC in CON did not change significantly over time ( $p \leq 0.05$ ; Figure 2A). The results indicate that non-labile-C remarkably influenced by different agricultural strategies. The non-labile-C content followed the order of  $\text{ORG} > \text{INT} > \text{CON}$ , and were based on the change in SOC and labile-C, which were decreased during the winter and increased during summer cultivations (Figure 2C).

#### 3.2. Effect of crop rotation systems on SOC fractions

Our results reveal that over time, the B-W crop rotation system with the value of  $5.7 \text{ g kg}^{-1}$  resulted in the highest SOC. In addition, statistically no significant ( $p \leq 0.05$ ) differences observed in SOC under F-W over time compared to all crop rotation systems that comprised summer crops in rotation with wheat (fallow-wheat rotation). The variation of SOC dynamics was similar for C-W and S-W crop rotation systems over time (Figure 3A). Regarding labile-C, the four crop rotation systems exhibited substantial differences between summer and winter. The S-W rotation in winter 2019 with  $1.9 \text{ g kg}^{-1}$  and the B-W crop rotation in winter 2019 and 2020 with 1.97 and  $2 \text{ g kg}^{-1}$ , respectively, yielded the highest amounts of labile-C. By contrast, in summer 2018, the amount of labile-C did not exhibit notable differences among the crop rotation systems, whereas it was significantly lower than that of similar crop rotation systems over time (Figure 3B). Similar to SOC and labile-C, the non-labile-C was the highest (significant level of

**TABLE 3** Results of analysis of variance (ANOVA) and levels of significance for the effect of seasonal weather variations (WV), agricultural strategy (A), crop rotation system (CR) and their interactions on the SOC, labile-C, and non-labile-C during 2018–2020 at the experimental plots near Ahvaz city in Khuzestan province in Iran.

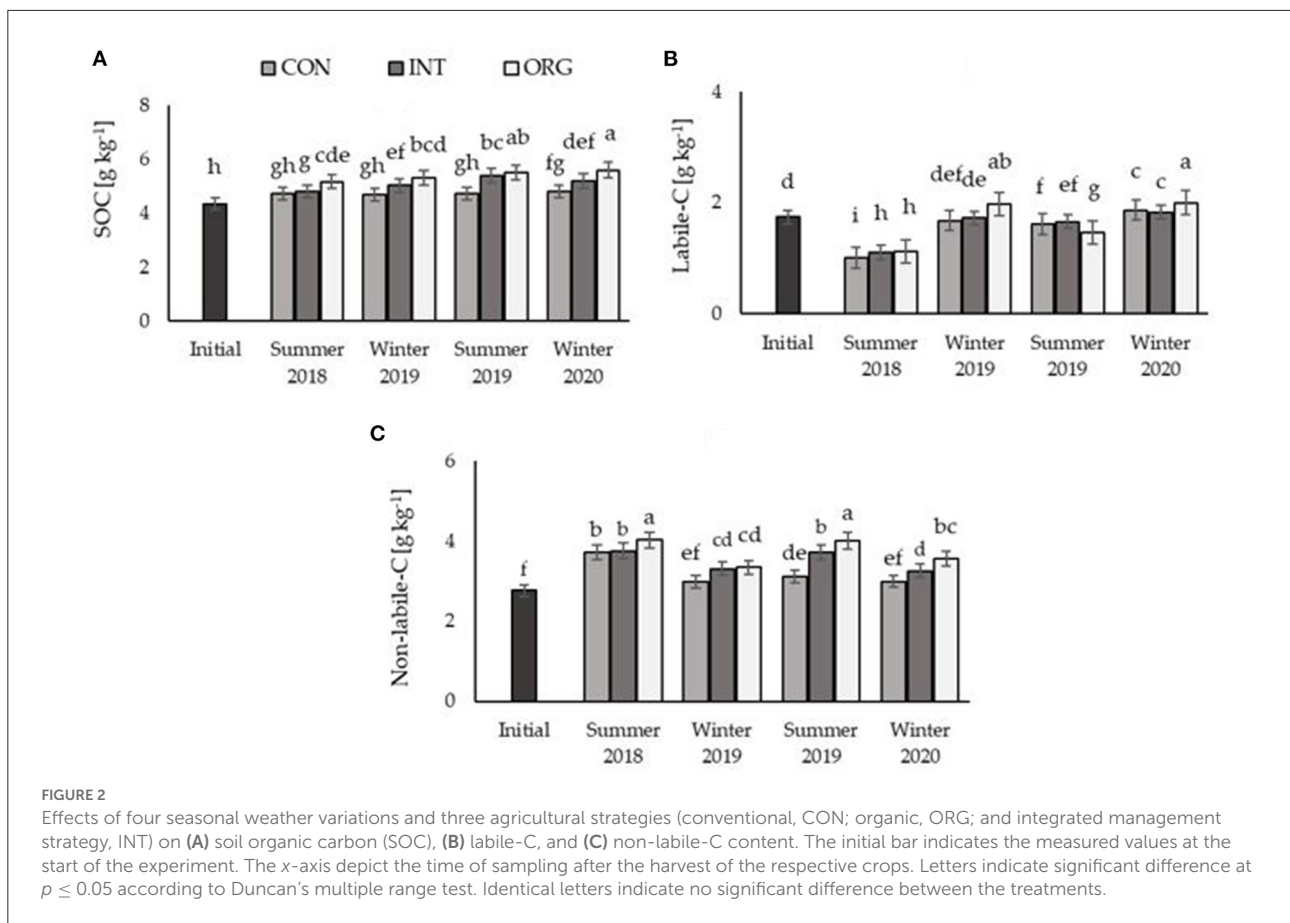
Source	df	SOC	Labile-C	Non-labile-C
Seasonal weather variations (WV)	4	0.027**	0.038**	0.06**
Error WV (WV × R)	10	0.0016	0.0001	0.0018
Agricultural strategy (A)	2	0.041**	0.0015**	0.027**
A × T	8	0.0042**	0.0013**	0.0037**
Error A × WV (A × WV × R)	20	0.014	0.00007	0.0014
Crop rotation system (CR)	3	0.051**	0.0014**	0.042**
WV × CR	12	0.0037**	0.00086**	0.0038**
A × CR	6	0.0078**	0.001**	0.007**
WV × A × CR	24	0.0014*	0.00073**	0.0018*
Error	90	0.00086	0.00009	0.00099
C.V		5.9	6.06	9.42

\* and \*\* indicate the significant level at  $p \leq 0.05$  and  $p \leq 0.01$ , respectively, by Duncan test based on the statistical design of mixed split-plot.

$p \leq 0.01$ ) in the B-W crop rotation system. In contrast to the amount of labile-C, the amount of non-labile-C was low during winter and high during summer. However, the lowest values of non-labile-C were observed for F-W in the winter of both 2019 and 2020 with 2.8 and  $2.6 \text{ g kg}^{-1}$ , values that were significantly lower than those of other crop rotation systems (Figure 3C).

#### 3.3. Interaction of weather variation, agricultural strategy, and crop rotation system on SOC fractions

A mean comparison of the triple interaction of the experimental treatments revealed an increasing trend in the content of SOC over time (relative to the initial SOC) in ORG and INT under all crop rotation systems except F-W (Figures 4A, D). In CON under all crop rotation systems, no significant differences in terms of SOC content compared to the initial value ( $p \leq 0.05$ ) were observed, except for the B-W crop rotation system, in which a 0.057% increase in SOC was observed after the summer 2019 and winter 2020 (Figure 4D). For the F-W crop rotation system (among all other agricultural

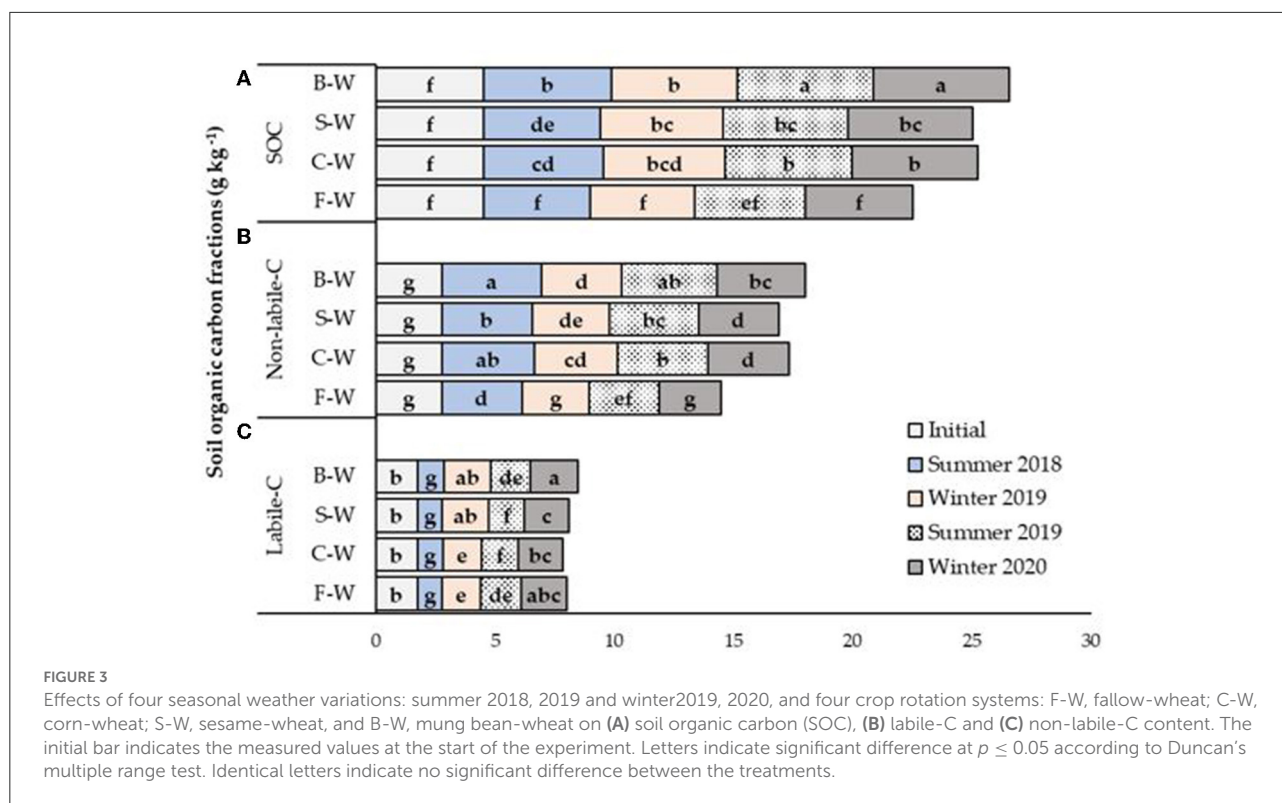


strategies) no significant difference was observed, except for INT in summer 2019, in which the amount of SOC ( $5 \text{ g kg}^{-1}$ ) was significantly higher than in the other agricultural treatments. In addition, the highest amount of SOC was observed in ORG ( $6.6$ ,  $5.7$ , and  $5.7 \text{ g kg}^{-1}$  for B-W, C-W, and S-W, respectively), followed by INT ( $5.5$ ,  $5.5$ , and  $5.3 \text{ g kg}^{-1}$ , for B-W, C-W, and S-W, respectively), and CON ( $5.1$ ,  $4.7$ , and  $5 \text{ g kg}^{-1}$  for B-W, C-W, and S-W, respectively; Figures 4B–D). Overall, the highest and lowest SOC values were observed for B-W ( $6.6 \text{ g kg}^{-1}$ ) and F-W ( $4.2 \text{ g kg}^{-1}$ ), respectively (Figures 4A, D).

The annual changes of SOC sequestration revealed that the F-W crop rotation system in ORG exhibited the lowest SOC content with a value of  $0.05 \text{ t C ha}^{-1} \text{ year}^{-1}$  (Table 4). However, C-W in INT exhibited a relative increase of 0.15% and was as effective as the B-W crop rotation in annual SOC sequestration in the soil with a value of  $1.49 \text{ t C ha}^{-1} \text{ year}^{-1}$  (Table 4).

For both years and all agricultural strategies and crop rotation systems, a non-significant increase in the amount of labile-C was observed (relative to the baseline value), especially after harvesting winter wheat (Supplementary Figures S2A, D).

However, in most cases, the amount of labile-C declined after the summer harvest. Although no significant difference was observed between the winters of 2019 and 2020 in terms of labile-C ( $p \leq 0.05$ ), the values measured in the second year indicate an increase over time. Similar to SOC, the labile-C content exhibited the highest value ( $2.3 \text{ g kg}^{-1}$ ) in ORG under the B-W crop rotation system (Supplementary Figure S2D), whereas the lowest value was observed in summer 2018 in the S-W and C-W crop rotation systems in CON and ORG ( $0.9 \text{ g kg}^{-1}$ ; Supplementary Figures S2B, C). For most of the crop rotation systems, a higher amount of non-labile-C was observed in ORG and INT. By contrast, in the S-W crop rotation system in INT, non-labile-C decreased over time compared to that in CON. Similar as in SOC and labile-C, the highest value of non-labile-C ( $4.5 \text{ g kg}^{-1}$ ) was observed in ORG in the B-W crop rotation system (Supplementary Figure S3D). Overall, our analysis of the experimental treatments demonstrates that the amount of non-labile-C increased over time (Supplementary Figures S3A, D), except in the F-W rotation system under INT, in which the lowest amount of non-labile-C ( $2.2 \text{ g kg}^{-1}$ ) was observed (Supplementary Figure S3A).



## 4. Discussion

### 4.1. Impact of weather variation on the SOC fractions

The weather condition in Khuzestan provided us this opportunity to monitor the change in soil labile-C under two different growing seasons in 1 year. Our results revealed that the amounts of labile-C under all crop rotation systems and agricultural strategies were reduced during high temperatures in summer cultivation (Supplementary Figure S2). Similar findings were reported by Lal (2015) and Naresh et al. (2018). The negative correlation between labile-C and high temperatures may strongly linked with the decomposition rate of organic matter and the increase in soil respiration (Fang et al., 2005; Luo et al., 2017). In summer, high temperature led to increased water evaporation from the irrigated soil under crop cultivation. Therefore, in low soil moisture the activity of microorganisms and organic matter decomposition decreased (Van Veen and Kuikman, 1990; Sierra et al., 2015). Remoistening the soil through crop irrigation has probably resulted in opportunistic using of organic matter by soil microorganisms and acceleration of organic matter decomposition. Consequently, the content of labile-C reduced due to its release from the soil in the form of  $\text{CO}_2$ . A study conducted by Thakur et al. (2018) delineated that high temperature (more than  $43^\circ\text{C}$ ) and low precipitation led to depletion of SOC pools due to increased soil respiration.

This situation was more apparent under ORG in summer 2019 in which a high level of decomposing crop residues, compost and vermicompost accumulated over time. In contrast with summer, temperate weather and distribution of precipitation during growing winter wheat provided the conditions required for sequestering C released by the decomposition of organic matter (Carvalhais et al., 2014).

### 4.2. Impact of agricultural strategy on the SOC fractions

Our findings revealed that the different agricultural strategies in combination with crop rotation systems played a crucial role in building up SOC, dynamics of C fractions, and significantly contributed to C-sequestration in the soil. The effects clearly differed among agricultural strategies and crop rotation systems. In all agricultural strategies and crop rotation systems, a positive relationship between SOC and labile-C was observed. Improving SOC in the soil surface (0–30 cm) in ORG and INT illustrated that these strategies are potentially effective approaches for sequestering C in soil in such a semi-arid agricultural region. Increasing the presence and decomposition rate of organic matter over time through adding bio and organic (compost/vermicompost) fertilizers as well as returning 30% of crop residues in the soil in ORG and applying



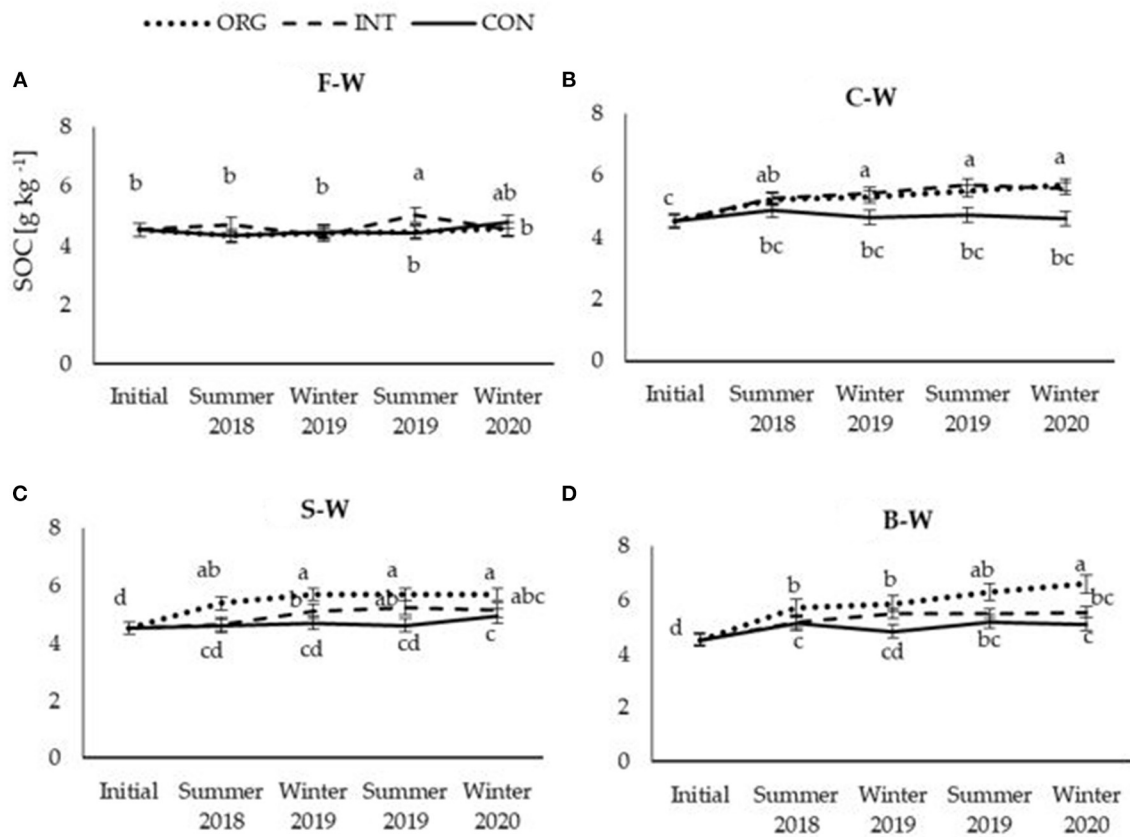


FIGURE 4

Interaction effects of four seasonal weather variations, three agricultural strategies (conventional, CON; organic, ORG; and integrated management strategy, INT), and four crop rotation systems: (A) F-W, fallow-wheat; (B) C-W, corn-wheat; (C) S-W, sesame-wheat, and (D) B-W, mung bean-wheat, on SOC change. The initial point indicates the measured values at the start of the experiment. The years depict the harvest time for winter and summer crops. Letters indicate a significant (different letters) and no significant (Identical letters) difference at  $p \leq 0.05$  according to Duncan's multiple range test.

half doses of them in INT could be the main reasons for this improvement. According to [Abdelhafez et al. \(2018\)](#), organic matter derived from manure had stable organic compounds during decomposition and remained safe from respiration. Therefore, they significantly improved C sequestration and boosted C pools in farmlands in the semi-arid regions. The application of inorganic fertilizer in combination with organic inputs in INT improved root and shoot biomass and enhanced SOC and its fractions through higher return of above and below ground residues in the soil ([Cambardella and Elliott, 1992](#); [Six et al., 2002](#); [Bhattacharyya et al., 2012](#)). CON also exhibited a positive effect over time through producing abundant plant biomass in shoots and root organs during plant growth and retaining root and additional plant residues in the soil. This is consistent with the results of [Rudrappa et al. \(2006\)](#) and [Liu et al. \(2013\)](#). The differences in labile-C among various agricultural strategies can be associated with various factors. One of these might be the close link of labile-C with the amount and types of crop residue returned to the soil. In fact, the

decomposition rate of crop residues (root and shoot) is one of the key factor explaining differences among labile-C values. For example leguminous residues with low C/N ratios aid in alleviating nitrogen limitations and are a substrate of accessible C for an extend range of microbial taxa leading to increased rates of labile-C fraction ([Fortuna et al., 2003](#); [Culman et al., 2013](#)).

#### 4.3. Impact of weather variation and crop rotation system on SOC fractions

Continuous crop rotation systems always resulted in high SOC content compared with F-W. This confirms the positive role of crops for C-sequestration. Maintenance and accumulation of crop roots and their incompletely decomposed residues near the soil surface is one of the most beneficial effects of wheat crop rotation systems with summer crops on C sequestration in agricultural lands ([Bremer and Ellert, 2008](#)).

TABLE 4 Average rate of increase in SOC ( $\text{t C ha}^{-1} \text{ year}^{-1}$ ) after 24 months (2018–2020).

Crop rotation	SOC [ $\text{t C ha}^{-1} \text{ year}^{-1}$ ]		
	CON	INT	ORG
F-W	0.10	0.10	0.05
C-W	0.25	1.50	1.56
S-W	0.68	1	1.57
B-W	0.85	1.49	2.20

Differences in SOC and labile-C changes between crop rotation systems can be owing to the different quantity and quality of returned crop residues. For example, high levels of root biomass production in the cereal-dominated rotation systems (here corn-wheat crop rotation system) with the above content of less-decomposable cellulose in their residues and high C/N ratio may contribute to a remarkable quantity of SOC over time (Ghosh et al., 2016; Islam et al., 2022). In addition, improvement of SOC and labile-C through the inclusion of legumes (B-W; in this study mung bean) in the rotation with wheat might be attributable to an increase in the rate of residue decomposition (i.e., the C/N ratios of involved crops). Similar findings have been reported in the literature (Drury and Tan, 1995; Gregorich et al., 2001; Parihar et al., 2018). Legumes also exert a positive effect on the rhizosphere through their root traits, which can improve the process of C-sequestration and also the turnover of labile-C in the topsoil (Fu and Cheng, 2002; Wu et al., 2017). Yet, because of the limited growth period of legumes, the interaction of plant roots with the soil leading to decreased soil hardness, amelioration of root extension, and improvement of soil bioactivity in the various crop rotation systems, returning their residues to the soil might be more effective in promoting SOC and labile-C than merely their growth (Whitbread et al., 2000; Blanco-Moure et al., 2016; Bongiorno et al., 2019).

#### 4.4. Interaction effect of weather variation, agricultural strategy, and crop rotation system on SOC fractions

The C-W crop rotation system in combination with organic and inorganic fertilizers was as effective as B-W on the annual SOC sequestration in the soil. As was reported by Gong et al. (2009) under C-W cultivation, the incorporation of inorganic fertilizer with manure through an increase in crop root biomass and crop stubble exerted a considerable positive influence on SOC improvement. In general, low SOC observed in F-W could be related to both agricultural management strategy and crop rotation system treatments. Bare soil in the summer (high temperature), as well as reduced entry of root and shoot crop residues (Maia et al., 2007) in combination with

organic matter (ORG and INT) into the soil could be two important reasons that caused a slight change in C-sequestration during the experimental times in F-W under all agricultural strategies. The negative effect of high temperature was also apparent in the relatively lower improvement of SOC in F-W for ORG. High temperature and summer fallow caused probably an increased C emission from the soil due to the increased decomposition rate of organic matter (Pei et al., 2017). It seems that temperature sensitivity to SOC decomposition was decreased by placing the summer crops in different rotation systems.

Furthermore, the capacity of plants for C-sequestration under distinct agricultural strategies depends on the growth and expansion of crop canopy (Aquino et al., 2017), which affects the relative change of non-labile-C to labile-C. In C-W, for example, we observed lower values of labile-C of summer corn in ORG compared with that in CON or INT, which might be due to the low initial growth of corn in this treatment as well as low decomposition of its residues due to high level of C/N ratio. This resulted in a high portion of non-labile-C in the soil. Finally, the duration for which plants were present on the farm is crucial and must be considered. A shorter growing season in summer compared to that in winter could be a reason for the variation of SOC and its fractions (Diekow et al., 2005; Majumder et al., 2008).

## 5. Conclusion

Our results demonstrated that although, the agricultural strategies based on crop residue management and organic fertilizer were more effective for C-sequestration, at high temperature and zero precipitation, accumulation of organic matter over time similar to ORG condition led to a greater reduction in labile-C pools. The comparison of various oil seeds, legumes, and cereal crops in rotation with wheat revealed a positive effect of B-W followed by C-W and S-W on SOC and C-fractions and exhibited superior performance compared with leaving the plots fallow. To have more details of the positive role of crops in C-sequestration, it is also important to consider the amount of C derived from roots and shoots (Huang et al., 2021). Our experiment did not specifically tackle this point (this was beyond the scope experiment). We recommend that additional researches should investigate the effect of temperature and different levels of nutrient management on soil C dynamics in the semi-arid regions. It can help to find an effective boundary between agricultural strategies and high temperature on C pools retention. More detailed results can be generated by conducting longer experiments and using agroecosystem modeling that involves climate-change scenarios at broader spatial scales. Increasing the time span of experiments would aid in exploring the role of climatic changes on the effectiveness of various treatments.

## 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

AG: writing, conceptualization, methodology, data collecting, and data processing. BK and TG: writing, review and editing, and data processing. AA and AR: methodology and data collecting. All authors listed contributed to the article and approved it for submission.

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## 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.

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## Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2022.1016000/full#supplementary-material>

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