Received: 3 October 2023 | Revised: 9 December 2023 | Accepted: 9 January 2024

DOI: 10.1002/fes3.522

REVIEW

Food and Energy Security Open Access WILEY

Determinants of the accuracy of using carbon isotopes in estimating water use efficiency of selected cereal and legume crops: A global perspective

Maltase Mutanda[1,2] | **Vincent Chaplot**[2,3] | **Hussein Shimelis**[2] | **Kwame W. Shamuyarira**[2] | **Sandiswa Figlan**[1]

[1]Department of Agriculture and Animal Health, University of South Africa, Florida, South Africa

[2]School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, South Africa

[3]Institut de Recherche pour le Dévelopement (IRD), Laboratory of Oceanography and Climate, Experiments and Numerical Approaches (LOCEAN), UMR 7159, IRD/C NRS/UPMC/MNHN, IPSL, Paris, France

Correspondence
Sandiswa Figlan, Department of Agriculture and Animal Health, University of South Africa, Florida 1709, South Africa.
Email: figlas@unisa.ac.za

Funding information
Water Research Commission, Grant/Award Number: C2020/2021-00646

Abstract

Field assessments of crop water use efficiency (WUE) are resource-consuming since they require simultaneous assessment of the total amount of water assimilated by crops for biomass and/or grain production. Alternative methods exist, such as estimating the carbon isotopic ratio ($^{13}C/^{12}C$) of the crop's leaf, aboveground biomass, or grain samples. There is limited information on the determinants of the accuracy of carbon isotopes in estimating water use efficiency between crop types and environments. Therefore, this study aimed to evaluate the extent to which the estimation of the $^{13}C/^{12}C$ ratio in crop parts constitutes an accurate proxy of WUE, globally. Data on observed WUE (WUE_{obs}) were collated involving 518 experiments conducted worldwide on major cereals and legumes and compared with WUE estimates (WUE_{est}) from carbon isotopes. The mean WUE_{obs} among all experiments was 3.4 g L^{-1} and the mean absolute error (MAE) was 0.5 g L^{-1} or 14.7% of WUE_{obs}, corresponding to accurate predictions at $p < 0.05$. However, the percentage mean absolute error of observed water use efficiency (%MAE) estimated from grains was 3.6 ± 11.5%, which was lower than the %MAE from aboveground biomass collected at harvest (3 ± 22.8%). In addition, the %MAE increased from 1.1 ± 5.1% for soybean, 1.6 ± 7.2% for maize, 1.2 ± 8.6% for rice, 1.8 ± 12.1% for groundnut, 2.1 ± 14.3% for cowpea, 2.3 ± 16.2% for bush bean, 1.8 ± 19.9% for wheat, 2.2 ± 21.4% for barley to 6.3 ± 39.3% for oat, with only the latter corresponding to significant errors. WUE_{est} were, in all cases, unbiased but slightly overestimated from 0.8% (maize) to 15.4% (oat). The accuracy in estimating WUE significantly decreased with the increase in soil clay content, with sand, showing a positive correlation of 0.3 with %MAE, but negatively correlated with the silt content ($r = -0.4$). Furthermore, a multivariate analysis pointed out a tendency for prediction errors and bias to increase with the decrease in WUE_{obs} and air temperature. Using carbon isotopes for estimating crop WUE thus appeared reliable for all crops and world environments, provided grain samples are considered. The technique tended to perform better under high WUE conditions, such as those generally found in maize and soybean cropping systems. The identified factors that affect the accuracy of using carbon isotopes in measuring WUE provide valuable insights for water resource management and sustainable crop production. These findings contribute to the ongoing discourse on water conservation strategies in agriculture, offering a basis for decision-making in crop improvement programs. Implementing the recommended practices from this study can potentially improve yield gains and promote resilient and sustainable agricultural systems in the changing environmental circumstances. Further research should investigate the mechanisms that cause low accuracy of the isotopic technique using aboveground biomass and under arid and cool environments.

KEYWORDS

carbon isotopic ratio, cereal crops, estimated water use efficiency, legume crops observed water use efficiency

1 | INTRODUCTION

Adopting water-saving technologies in agriculture and developing crop varieties with high water use efficiency (WUE) reduces crop water demand whilst increasing the productivity and resilience of farming systems (Fang et al., 2010). The concept of WUE was first introduced by Briggs and Shantz (1913) to link water consumption and crop outputs. Agronomists define WUE as the ratio of crop product (e.g., biomass or grain yield) per unit of rainfall or irrigation water used (Martínez & Reca, 2014). Furthermore, plant physiologists have defined WUE as the amount of carbon assimilated as crop biomass per unit of water lost through a combination of evaporation and transpiration (Hoover et al., 2023).

Crop WUE can be assessed using several methods (Kugedera et al., 2022; Mbava et al., 2020). Measuring WUE based on plant biomass requires destructive sampling and drying until the constant weight of plant materials is achieved. The amount of water used is to equal the total rainfall during the critical crop-growing cycle (Kugedera et al., 2022). Changes in soil water content can be measured using gravimetry (i.e., drying and weighing of soil samples of a known volume) or soil humidity sensors or probes (e.g., time domain reflectometry sensors and electromagnetic sensors) to estimate the amount of water used by crop plants. Crop evapotranspiration (ET) can also be estimated from meteorological data, such as air temperature, air humidity, wind speed, and quantity of water applied through irrigation or rainfall, all being recorded from a standard weather station. In addition, evapotranspiration can also be computed based on air temperature, relative humidity, wind speed, and solar radiation using the Penman-Monteith method (da Silva et al., 2013). Despite this, estimating crop WUE using classical methods remains resource-consuming and expensive, especially when long durations are considered or in extensive field experiments with multiple genotypes under many treatments. Skilled personnel are also required to install, calibrate, and maintain a suite of equipment for collecting and computing the acquired data.

Several researchers have devised alternative methods of estimating WUE. These include plant-air gas exchange technologies (Guerrieri et al., 2019), chlorophyll fluorescence (Shan et al., 2021), and carbon isotope discrimination (Pronger et al., 2019). Gas exchange techniques such as leaf-level photosynthesis and transpiration rate measurements require infrared gas analyzers to simultaneously monitor CO_2 uptake and water loss. They estimate WUE as the ratio between carbon assimilation and water loss. Chlorophyll fluorescence is a non-destructive method measuring the fluorescence emitted by leaves when the chlorophyll absorbs light. These methods that reflect the plant stress caused by water scarcity require multiple fluorometer measurements. However, these techniques can be of low accuracy since the results appear highly dependent on light intensity and leaf age (Yin et al., 2011). Carbon isotope discrimination is a relatively easy and economical method to assess crop WUE as it only requires estimating the carbon isotopic ratio ($^{13}C/^{12}C$) through mass spectrometry analysis of crop samples such as from leaf, aboveground biomass, or grain (Engoke et al., 2022; Farquhar et al., 1989; Ma et al., 2020). When plants assimilate carbon dioxide (CO_2) from the atmosphere through photosynthesis, they discriminate against the heavier ^{13}C isotope and preferentially fix the lighter ^{12}C isotope (Eggels et al., 2021; Zheng et al., 2020). This results in a lower ratio of ^{13}C to ^{12}C in the plant tissues compared with the atmospheric CO_2. The degree of this discrimination is influenced by the environmental conditions (including temperature, humidity, and rainfall) and soil properties (including bulk density, pH, and texture) in which the plant grows. Plants with a greater proportion of CO_2 fixation per daytime stomatal water loss tend to have higher ratios of ^{13}C to ^{12}C in their tissues.

In the past two decades, several studies have assessed WUE using carbon isotopes for different crops and environmental conditions (Arslan et al., 1999; Avramova et al., 2019; Wang et al., 2016; Zhang et al., 2015). However, the correlation between WUE and the carbon discrimination ratio (CID) varied primarily among studies. For instance, in the temperate region of Austria, Arslan et al. (1999) reported a negative correlation of WUE and CID for wheat (r = −0.85), while Zhao et al. (2009) in China highlighted a positive correlation for the same crop (r = 0.54). In India, Rao et al. (1993) pointed out a significant negative correlation between WUE and CID in groundnut (r = −0.66), while in maize, Yang and Li (2018) found a negative correlation (r = −0.67) under low rainfall conditions in China. Furthermore, a low correlation of WUE and CID (r = 0.19) was reported in China by Zhang et al. (2015) for maize. In Canada, Raeini-Sarjaz et al. (1998) reported a significant negative relationship between CID and WUE (r = −0.88) in bush beans. A study by Raeini-Sarjaz and Chalavi (2008) reported correlations of CID and WUE at r = −0.72 and r = −0.75 on bush beans under open air and perforated plastic house growing conditions, respectively.

While the use of CID to estimate WUE is paramount, the differences and inconsistencies in the strength and directions of the relationships between WUE_{obs} and CID for different crops, environmental factors, and soil properties make it difficult to conclude the overall accuracy of using carbon isotopes. A comprehensive analysis of data compiled from experiments conducted worldwide may provide information on the determinants of the reliability of using CID to estimate WUE. Several studies examined only the magnitude of the correlation between WUE and CID in cereal crops and legumes as a selection criterion. That does not provide a detailed account of the accuracy of using CID for direct or indirect measurement and crop type selections. There is a need to compare data based on observed WUE and CID-based WUE estimates to ascertain measurements and optimal water use and crop performance predictions. There is limited information on the determinants of the accuracy of carbon isotopes in estimating water use efficiency between crop types and environments. Therefore, this study aimed to evaluate the extent to which the estimation of the $^{13}C/^{12}C$ ratio in crop parts constitutes an accurate proxy of WUE globally.

2 | MATERIALS AND METHODS

2.1 | Study setup

The present study was based on the data of carbon isotopes used in estimating WUE in cereal and legume crops collected from the field and controlled environment experiments conducted globally. The articles were searched on electronic academic databases using the following search engines: Web of Science, Science Direct, SpringerLink, Scopus, Google Scholar, SciFinder, and ResearchGate. The following keywords were used to search for relevant articles: "legume crops", "cereal crops", "carbon isotope" and "water use efficiency." The quotation marks were used to search for the keywords as a whole, not each word alone. The search for articles was completed in December 2022. The articles were limited to reports on cereal and legume crops only, with no delimitations of the study period. For the articles to be included in the analysis, they had to report on direct measurements of observed water use efficiency (WUE_{obs}) and carbon isotope discrimination (CID). Data on the soil properties (soil pH, bulk density, and texture), crop variables (crop types and crop genotype), and environmental factors (mean annual precipitation, temperature, climatic regions, and continents) were captured (see Table S1). When soil and environmental data were not available in the selected articles, the data for those variables were extracted from the publications involving experiments conducted in the same area. After all the relevant studies meeting the selection criteria were selected, data was extracted and compiled into a Microsoft Excel database. The final database comprised 518 WUE_{obs} data points (observations) from 36 peer-reviewed journal articles (Table 1).

2.2 | Definitions of environmental factors

In this analysis, the climatic regions were categorized based on the mean annual precipitation (MAP) and mean annual temperature (MAT) and do not necessarily comply with the Köppen (1936) system. Those climatic categories were subtropical, tropical, temperate, arid, semi-arid, continental, and Mediterranean. Subtropical depicts warm (MAT: 10–30°C year^{-1}) and dry to wet (MAP: 100–1000 mm year^{-1}) climate; tropical represents hot (MAT: >20°C year^{-1}) and wet (MAP: >1000 mm year^{-1}) climate; temperate represents cool (MAT: <5°C year^{-1}) and dry (MAP: 0–800 mm year^{-1}) climatic zones. Arid represents hot (MAT: >20°C year^{-1}) and dry (MAP: 0–300 mm year^{-1}); semi-arid represents cool (MAT: <20°C) and dry (MAP: 0–300 mm year^{-1})

TABLE 1 Summary of a database of references used in the study showing the means of selected environmental factors.

No	Author	Crop name	Country	Climate	*N*	MAP (mm year^{-1})	MAT (°C)	WUEobs (g L^{-1})
1	Akhter et al. (2010)	Rice	Pakistan	Temperate	8	400	25	49
2	Akhter et al. (2012)	Wheat	Pakistan	Temperate	32	762	25	49
3	Anyia et al. (2007)	Barley	Canada	Temperate	46	534	10	134
4	Arslan et al. (1999)	Wheat	Austria	Temperate	18	413	11	11
5	Brunel-Saldias et al. (2018)	Oat	Chile	Mediterranean	5	430	15	4
6	Cai (1992)	Wheat	United States	Temperate	48	322	15	324
7	Chen et al. (2011)	Barley	Canada	Temperate	8	193	10	38
8	Hafsi et al. (2009)	Wheat	Algeria	Subtropical	8	663	20	33
9	Heng et al. (2005)	Maize, Wheat	Argentina, China, India, Morocco	Arid, Semi-arid	54	283	10	56
10	Huang et al. (2019)	Wheat	China	Subtropical	12	173	12	19
11	Impa et al. (2005)	Rice	India	Tropical	6	925	32	15
12	Ismail and Hall (1993)	Cowpea	US	Temperate	32	279	15	136
13	Javed et al. (2012)	Rice	Pakistan	Temperate	15	276	18	124
14	Jiang et al. (2020)	Soybean	USA	Temperate	11	458	12	38
15	Khazaei et al. (2008)	Wheat	Iran	Arid	3	234	24	9
16	Kirda et al. (1992)	Wheat	Austria	Temperate	4	413	19	17
17	Knight et al. (1994)	Wheat	Canada	Temperate	20	534	10	28
18	Liu et al. (2020)	Wheat	China	Subtropical	8	92	13	15
19	López-Castañeda and Richards (1994)	Barley	Australia	Subtropical	12	309	22	55
20	Thameur et al. (2018)	Barley	Tunisia	Mediterranean	10	158	21	35
21	Nadaradjan et al. (2005)	Rice	India	Tropical	4	925	32	17
22	Raeini-Sarjaz and Chalavi (2008)	Bush bean	Canada	Temperate	18	23	17	90
23	Raeini-Sarjaz et al. (1998)	Bush bean	Canada	Temperate	3	534	10	6
24	Rao et al. (1993)	Groundnut	India	Tropical	10	187	35	18
25	Shaheen and Hood-Nowotny (2005)	Wheat	Austria	Temperate	32	413	19	74
26	Tobita et al. (2007)	Soybean	Brazil	Temperate	8	1900	27	26
27	White et al. (1996)	Soybean	Australia	Temperate	12	706	30	26
28	Wright and Rao (1993)	Groundnut	Australia	Tropical	16	706	30	45
29	Wright et al. (1994)	Groundnut	Australia	Tropical	8	706	30	21
30	Yang and Li (2018)	Maize	China	Subtropical	6	389	10	11
31	Kang et al. (1996)	Barley	Australia	Continental	8	636	19	20
32	Zhang et al. (2010)	Wheat	Canada	Tropical	8	534	10	79
33	Zhang et al. (2015)	Maize	China	Subtropical	3	149	10	24
34	Zhang et al. (2019)	Wheat	China	Subtropical	10	180	15	32
35	Zhao et al. (2004)	Rice	Japan	Subtropical	6	1000	14	17
36	Zhao et al. (2009)	Wheat	China	Subtropical	12	328	16	59

Abbreviations: MAP, mean annual precipitation; MAT, mean annual temperature; WUE_{obs}, observed water use efficiency.

climate; Mediterranean represents cool (MAT: <20°C) and dry (MAP: <400 mm year^{-1}); continental climates represent hot summers and cold winters (MAT: 0–20°C) and MAP (250–750 mm year^{-1}). When the information about MAP and MAT is not given in the papers, the MAP and MAT of the last 30 years for that particular area were used based on data gathered from climate-data.org (2021). The definitions of all environmental factors and soil properties considered in the study are presented in Table 2. The soil textural classes are categorized into three classes: clay loam, loam, and sandy soil based on the percentage of clay, sand, and silt in the soil, in that order. When the data for the soil properties is not given, the data from other studies conducted in the same area was used. The classification of all environmental factors and soil properties are summarized in Table 3.

2.3 | Definitions for the WUE_{obs} and CID

The present study adopted the definition of WUE_{obs} as the amount of total plant biomass production (expressed in g plant^{-1}) per unit of water applied in liters (L) either through irrigation or rainfall (Meißner, 2021; Parmoon et al., 2022). The data for WUE_{obs} were extracted from the papers and normalized to g L^{-1}. The CID was defined as the difference in the ratio of ^{13}C to ^{12}C in the atmospheric CO_2 and the organic compounds produced by the plant. The CID was recorded as given in the papers and standardized to per thousands. The CID is determined by analyzing leaf, aboveground biomass and/or grain samples that are dried at 60°C for 48 h and ground into fine powder. The carbon isotopic ratio of the samples (R_{sample}) and standard ($R_{standard}$), which is from the CO_2 obtained from a limestone from Pee Dee Belemnite "PDB" formation in South Carolina, USA are obtained using an isotope ratio mass spectrometer. R values are converted to $\delta^{13}C$ (in ‰ or per ml) using the relationship:

$$\delta^{13}C\,(‰) = \left[\frac{R_{sample}}{R_{standard}} - 1\right] \times 1000. \quad (1)$$

Then CID is determined using the relationship established by Farquhar et al. (1989):

$$CID = \left[\left(\delta^{13}C_a - \delta^{13}C_p\right) / \left(1 + \delta^{13}C_p\right)\right] \times 1000 \quad (2)$$

where $\delta^{13}C_a$ = isotope composition of atmospheric CO_2 and $\delta^{13}C_p$ = isotope composition of plant samples.

In cases where CID and WUE_{obs} values were not given explicitly in the text or tables, the data were estimated from the graphs that showed the relationship between WUE_{obs} and CID in the same article.

2.4 | Determination of estimated water use efficiency (WUE_{est}) and associated errors

In the present study, the WUE_{est} was defined as the ability of the plant to utilize water for photosynthesis, which was measured by examining the carbon isotopic composition in plant tissues. The two variables (WUE_{obs} and CID) were used to calculate the estimated water use efficiency (WUE_{est}) at each data point using the following general linear equation:

TABLE 2 Description of environmental factors and soil properties used in this analysis.

Environmental factors	Symbol	Units	Definitions
Mean annual precipitation	MAP	mm year^{-1}	Mean precipitation per year for the study location
Mean annual temperature	MAT	°C year^{-1}	Mean temperature per year for the study location
Soil Bulk density	BD	g cm^{-3}	Bulk density of the topsoil layer (0–30 cm)
Soil pH	pH		The pH of the topsoil layer (0–30 cm) as given in papers at that location
Clay content	Clay	%	Average clay content (or fine-textured soil particles) of the topsoil (0–30 cm)
Sand content	Sand	%	Average sand content (or coarse textured soil particles) of the topsoil (0–30 cm)
Silt content	Silt	%	Average silt content (or medium textured soil particles) of the topsoil (0–30 cm)
Nitrogen	N	mg kg^{-1}	Nitrogen content of the topsoil (0–30 cm) as given in papers
Phosphorus	P	mg kg^{-1}	Phosphorus content of the topsoil (0–30 cm) as given in the papers
Potassium	K	mg kg^{-1}	The potassium content of the topsoil (0–30 cm) as given in the papers

TABLE 3 List of classes describing the environmental factors, crop types, soil properties, and continents used in the analysis.

Environmental factors	Remarks	Class range	Name
Soil pH	Soil pH of the topsoil horizon (0–30 cm) as given in the articles	<5	Highly acidic
		5.1–6.5	Acidic
		7.0–8.0	Basic
		>8	Highly basic
Clay %	The average clay content of topsoil horizon (0–30 cm)	0%–20%	Low
		21%–40%	Medium
		>40%	High
Sand %	The average sand content of the topsoil horizon (0–30 cm)	0%–25%	Low
		26%–50%	Medium
		>50%	High
Silt %	The average silt content of the topsoil horizon (0–30 cm)	0%–20%	Low
		21%–40%	Medium
		>40%	High
Soil bulk density	The density of the topsoil (0–30 cm)	$<1.4\,g\,cm^{-3}$	Low
		$>1.4\,g\,cm^{-3}$	High
Climatic regions	Hot and wet	MAP: $>1000\,mm\,year^{-1}$ MAT: $>20°C\,year^{-1}$	Tropical
	Dry to wet	MAP: 300 to $1000\,mm\,year^{-1}$ MAT: 10 to $20°C\,year^{-1}$	Subtropical
	Cool and moist	MAP: $<800\,mm\,year^{-1}$ MAT: 1.2 to $18.6°C\,year^{-1}$	Temperate
	Warm and dry	MAP: 100 to $300\,mm\,year^{-1}$ MAT: 3.5 to $31.9°C\,year^{-1}$	Arid
	Cool and dry	MAP: 300 to $550\,mm\,year^{-1}$ MAT: −2.3 to $25°C\,year^{-1}$	Semi-Arid
	Warm and wet	MAP: $<400\,mm\,year^{-1}$ MAT: $<20°C\,year^{-1}$	Mediterranean
	Hot summers and cold winters	MAP: 250 to $750\,mm\,year^{-1}$ MAT: 0 to $20°C\,year^{-1}$	Continental
Crop type	Grain crops	Maize, wheat, rice, barley, oat	Cereals
	Legume crops	Groundnut, Bush bean, Soybean, Cowpea	Legumes

$$WUE_{est} = M\,(CID) + k \tag{3}$$

where WUE_{est} = estimated water use efficiency; CID = carbon isotope discrimination per each data point, M = the gradient of the CID and WUE_{obs} values per each study (in cases where the study was conducted under different climates and on different crops, the values of M were calculated using CID and WUE_{obs} values per climate and crop), k = the *y*-axis intercept after generating the linear graph using CID and WUE_{obs} values (in cases where the study was conducted under different climates and on different crops), the values of k obtained from the linear equation using CID and WUE_{obs} values per climate and crop (see Tables S2 and S3).

The following parameters were calculated as a measure of the accuracy of WUE_{est} and were entered into the database (see Table S1): mean errors (ME), percentage mean errors (%ME), mean absolute error (MAE), percentage mean absolute error (%MAE), mean square error (MSE), root mean square error (RMSE). Calculations were based on the formulae:

$$ME = WUE_{est} - WUE_{obs} \tag{4}$$

where ME = mean error; WUE_{est} = estimated water use efficiency; WUE_{obs} = observed water use efficiency

$$\%ME = \frac{ME}{WUE_{obs}} \times 100 \tag{5}$$

where %ME = percentage mean error of observed water use efficiency; ME = mean error; WUE_{obs} = observed water use efficiency

$$\text{MAE} = \text{ABS}\left(\text{WUE}_{\text{est}} - \text{WUE}_{\text{obs}}\right) \quad (6)$$

where MAE = mean absolute; WUE_{est} = estimated water use efficiency; WUE_{obs} = observed water use efficiency; ABS = absolute value. Microsoft Excel 365 was used to calculate the MAE by entering ABS ($\text{WUE}_{\text{est}} - \text{WUE}_{\text{obs}}$) in the Excel sheet cell to make all the error values positive.

$$\%\text{MAE} = \frac{\text{MAE}}{\text{WUE}_{\text{obs}}} \times 100 \quad (7)$$

where %MAE = percentage mean absolute error of observed water use efficiency; MAE = mean absolute error; WUE_{obs} = observed water use efficiency

$$\text{MSE} = (\text{ME})^2 \quad (8)$$

where MSE = mean square error; ME = mean error

$$\text{RMSE} = \sqrt{\text{MSE}} \quad (9)$$

where RMSE = Root means square error; MSE = mean square error.

2.5 | Data analysis

Prior to statistical analysis, data were tested for normality, outliers, linearity, and homoscedasticity. Summary statistics describing mean, median, minimum, maximum, quartile 1 (25%), quantile 3 (75%), standard deviation, coefficient of variation (%CV), skewness (skew), and kurtosis (Kurt) were generated for water use efficiency variables and accuracy parameters (Table 4). Accuracy parameters were computed for different crop types, soil textural classes, and environmental factor classes. The boxplots showing the distribution of the accuracy parameters based on minimum, maximum, median, and the first and third quartile values after removing outliers were generated using IBM SPSS Statistics (Version 27). Bivariate analyses based on Spearman rank correlations were carried out in IBM SPSS Statistics (Version 27), which was also used to test the significant difference between WUE_{obs} and WUE_{est} in all crops, environmental factors, and soil properties. A multivariate analysis, using uncentred principal component analysis (PCA) was conducted to show the multiple relationships between the %ME, %MAE, MAP, MAT, clay, sand, pH, bulk density, WUE_{obs}, crops, plant parts, and continents in R statistical software.

TABLE 4 Summary statistics of environmental factors, soil properties, and error variables generated for this analysis.

Variables	Mean	Median	Min	Max	Q_1	Q_2	STD	CV%	Skew	Kurt
BD	1.4	1.4	0.6	1.8	1.3	1.5	0.2	14.4	−0.4	2.5
pH	7.3	7.5	4.9	8.2	6.9	7.8	0.7	9.8	−1.1	0.8
Clay	20.9	14.7	7.5	51	14.7	22	13.4	64.2	1.5	1.1
Sand	53.3	45	25	87.5	40	60.9	17.6	33	0,6	−0.4
Silt	25.8	24.4	5.1	64	12.7	33	14.8	57.3	0.8	0.9
MAP	431.6	410	22.6	1900	236	534	277	64.1	2.4	10.4
MAT	16.7	15	10	35	11.2	19.1	6.5	39	1.1	0.8
CID	2789	22.2	0	21,100	18.7	38.9	6589	236	2	2
WUE_{obs}	3.4	2.8	0.1	19	1.7	4.4	2.4	69.7	1.7	5.6
WUE_{est}	3.4	2.9	0.2	11.1	1.7	4.6	2.2	64.3	1	0.5
ME	0	0	−8.7	4.2	−0.2	0.3	0.9	16,966	−2.5	28.8
%ME	5.7	0.5	−51	304	−8.1	13.2	29.2	511	3.6	26.3
MAE	0.5	0.3	0	8.7	0.1	0.6	0.8	152	5.5	44.9
%MAE	17.2	10.4	0	304.1	4.6	22	24.2	140	5.4	46.6
MSE	0.8	0.1	0	74.9	0	0.4	4.5	553	13.1	193.6
RMSE	0.5	0.3	0	8.7	0.1	0.6	0.8	152	5.5	44.9
R^2	0.4	0.3	0.01	1	0.1	0.6	0.3	79.7	0.6	−0.8

Abbreviations: %MAE, percentage mean absolute error of observed water use efficiency; %MAE, percentage mean error of observed water use efficiency; BD, bulk density (g cm^{-3}); CID, carbon isotope discrimination (per thousands); CV, coefficient of variation; Kurt, kurtosis; MAE, mean absolute error; MAP, mean annual precipitation; MAT, mean annual temperature; max, maximum; ME, mean error; Min, minimum; MSE, mean square error; Q_1, lower quartile; Q_3, upper quartile; R^2, coefficient of determination; RMSE, root mean square error; Skew, skewness; STD, standard deviation; WUE_{est}, estimated water use efficiency (g L^{-1}); WUE_{obs}, water use efficiency (g L^{-1}).

3 | RESULTS

3.1 | Summary statistics for environmental, soil, and crop variables

The variations in environmental factors, soil properties, WUE and error variables are presented in Table 4. The WUE_{obs} have a relatively higher CV% (69.7%) than WUE_{est} (64.3%), indicating that estimated values have low variations. Among the error variables, only ME has a negative skewness (ME = −2.5), and values are skewed to the left. The %MAE varied widely across the study sites, as shown by a minimum and maximum value of 0 and 304, respectively.

3.2 | Crop type impact on the accuracy of using CID to estimate WUE

Legumes had a significantly lower mean %MAE (1 ± 11.9%) with values ranging from 0.03% to 64% than cereals (1.3 ± 19.3%), which ranged from 0.01% to 304% (Figure 1). Amongst cereals, maize had the lowest mean %MAE (1.6 ± 7.2%), followed by rice (1.2 ± 8.6%), while oats (6.3 ± 39.3%) had a significantly higher %MAE. Soybean had the lowest mean %MAE (1.1 ± 5.1%) among the legume crops. The level of error is highly variable for crops with C_3 (min = 0.01%; max = 304%) than with C_4 (min = 2%; max = 4.4%) photosynthesis. Across all the crops, soybean had the least variation of %MAE (min = 1.3%; max = 3.5%), whilst wheat (min = 0.01%; max = 304%) and barley (min = 0.1%; max = 127%) had the highest variation of %MAE (Figure 2). The ME exhibited that CID overestimates WUE in barley (ME = 0.01). Oat presented a high mean %MAE but low %MAE variation among all the assessed crops. The %MAE was not significantly different on soybean, cowpea, groundnut, maize, and rice at $p < 0.05$.

3.3 | Impact of plant part CID on the accuracy of WUE estimations

Among all the plant parts' CID, grain CID has the lowest %MAE (3.6 ± 11.5%) when estimating WUE, whilst aboveground biomass CID has the highest %MAE (3 ± 22.8%). The aboveground biomass had the highest variation %MAE, followed by leaf and grain samples (Figure 3). The data for ME exhibited that the use of aboveground CID appeared to overestimate WUE (ME = 0.01), and the t-value was negative (t = −0.03), indicating that WUE_{est} was greater than WUE_{obs}. There was non-significant difference between the %MAE for grain and leaf samples, but the median %MAE for the leaf was significantly higher than the grain.

3.4 | Impact of environmental conditions and soil properties on %MAE

3.4.1 | Soil texture

The boxplots (Figure 4) highlighted that the %MAE in each soil texture differs, with the sandy having the lowest mean %MAE of 1.3 ± 14% than on loam (1.1 ± 16.2%) and clay loam (2.8 ± 21.8%). The variation of %MAE is high for clay loam (Min = 0.01%, Max = 304%) and least for %MAE on sand soils (Min = 0.04%, Max = 127%). Data from ME show that carbon isotopes marginally underestimated WUE in loam (−0.01) and marginally overestimated WUE in clay loam (0.02) soils. The MAE is higher on loam soils (MAE = 0.6), and there is an underestimation of WUE (ME = −0.01). The MSE (0.3) on sandy soil is lower than the RMSE value (0.4). The t-value was negative and non-significant (t = −0.1) on sandy soil, indicating that WUE_{est} was greater than the WUE_{obs}.

3.4.2 | Climatic conditions

The overall mean of the %MAE was high under Mediterranean (8.3 ± 42.2%), semi-arid (3.2 ± 21.5%), and temperate (1.5 ± 17.7%) climates, but lower under arid (2.9 ± 8.6%) and subtropical (1.3 ± 9%) climates. The %MAE under the Mediterranean climate (8.3 ± 42.2%) is more than four times the %MAE under the arid climate (2.9 ± 8.6%). The variation of %MAE is higher under Mediterranean climates (min = 0.1%, max = 127%) followed by Semi-Arid (min = 0.2%, max = 118%) and lower variation recorded under arid (min = 0.8%, Max = 18%) climates (Figure 5). The ME exhibited that under continental climates, carbon isotopes overestimate WUE (ME = 0.3). There was a non-significant difference between WUE_{est} and WUE_{obs} under all the climates.

3.4.3 | Continental difference

Higher %MAE mean values were recorded in Europe (8 ± 35.4%), Africa (4.7 ± 26.9%), and South America (4.3 ± 16.5%), than in Asia (1.1 ± 13%) and Oceania (1.4 ± 11.2%). There is a higher variation of %MAE in Europe (min = 0.03% to max = 304) and the least variation in Oceania (1.4 ± 11.2%) (Figure 6). Among all the continents, WUE_{obs} and WUE_{est} were significantly different in Oceania only. The t-value comparing WUE_{obs} and

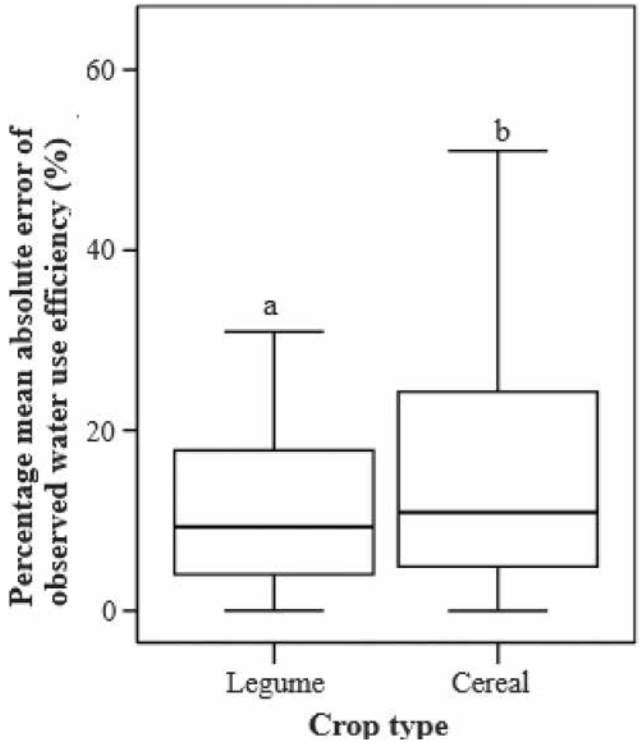

FIGURE 1 Boxplots comparing the percentage mean absolute errors (%MAE) of using carbon isotopes in estimating WUE in cereals and legumes. Each boxplot presents the minimum, maximum, median, quartile 1 (25%), and quartile 3 (75%) for percentage mean absolute errors. Box plots accompanied by similar letters were not significantly different at $p<0.05$.

WUE_{est} was negative and non-significant in Asia ($t=-0.1$) and Oceania ($t=-1.1$), suggesting that WUE_{obs} was lower than WUE_{est}.

3.5 | Correlation analysis

The Spearman correlation coefficients (Table 5) showed that the %MAE had positive and significant correlations with CID ($r=0.12$, $p<0.01$) and negatively correlated with WUE_{obs} ($r=-0.12$) and under silt soil ($r=-0.4$). The %MAE had weak correlations with the bulk density ($r=0.09$) and clay soil content ($r=0.09$).

3.6 | Principal component analysis

The interrelationships among the assessed parameters (environmental factors, soil properties, %ME, %MAE and WUE_{obs}, crops, plant parts, and continents) were explored by principal component analysis (PCA) (Figure 7). The PCA showed that the first principal component (PC1) explains 40.3% of the total variation and exhibited a higher positive association with sand and bulk density. The principal component 2 (PC2) accounted for 27.1% of the data variation and had a higher positive correlation with MAT and MAP and a negative correlation with %MAE, %ME and $WUE_{obs.}$ The %MAE was significantly and positively correlated with %ME in crop types, plant parts and continents. The crop (oat), continent (Europe) and plant part (aboveground biomass) where the %MAE appeared to be very high are in the same direction as %ME and %MAE. On the other hand, the crops, plant parts and continents with lower %MAE appear to be in the opposite direction of %MAE and %ME. Cereal crops with a low %MAE were in the same direction as $WUE_{obs.}$ The BD was positively correlated with %MAE and %ME on crops only (Figure 7), and in plant parts and continents, the BD is negatively correlated with both %MAE and %ME.

4 | DISCUSSION

4.1 | Crop type impact on the accuracy of carbon isotopes in estimating WUE

The level of accuracy when measuring crop WUE using carbon isotopes differs with crop type. The results of the present analyses showed that the %MAE was significantly lower in legumes (1 ± 10.9%) than in cereals (1.3 ± 19.3%) (Figure 1). The results could be ascribed to the legumes' nitrogen-fixing ability (Parniske, 2018), supplying the plant with a significant proportion of its nitrogen need. This allows the plant to use water more efficiently than cereals, which rely on soil nitrogen to a greater extent. Nitrogen utilization affects CID (Yin & Raven, 1998). Legumes can discriminate against ^{13}C isotopes better than cereals, making the estimation of WUE more accurate. Legume crops, especially the ones involved in this analysis (e.g., groundnut), are generally more drought-tolerant than some cereals (e.g., oats and rice) (Daryanto et al., 2017) enabling them to maintain photosynthesis and CID under low water availability conditions. In contrast, severe drought stress can strongly impact CID in cereals to a greater extent, causing the CID-based WUE estimates to be less accurate (Liu, 2016).

Among the cereals, plants with C_3 photosynthesis (e.g., wheat, rice, barley, and oats) have a higher %MAE than C_4 plants (e.g., maize) (Figure 2). The differences in the %MAE between C_3 and C_4 cereals could be explained by their differences in photosynthetic pathways since the relationship between plant WUE and CID relies on the CID between ^{12}C and ^{13}C that occurs during the incorporation of CO_2 into plants (Santesteban et al., 2015). The results highlighted that maize had low %MAE than other C_3 cereals. This is attributable to maize having a special and unique photosynthetic pathway that allows water use more efficiently

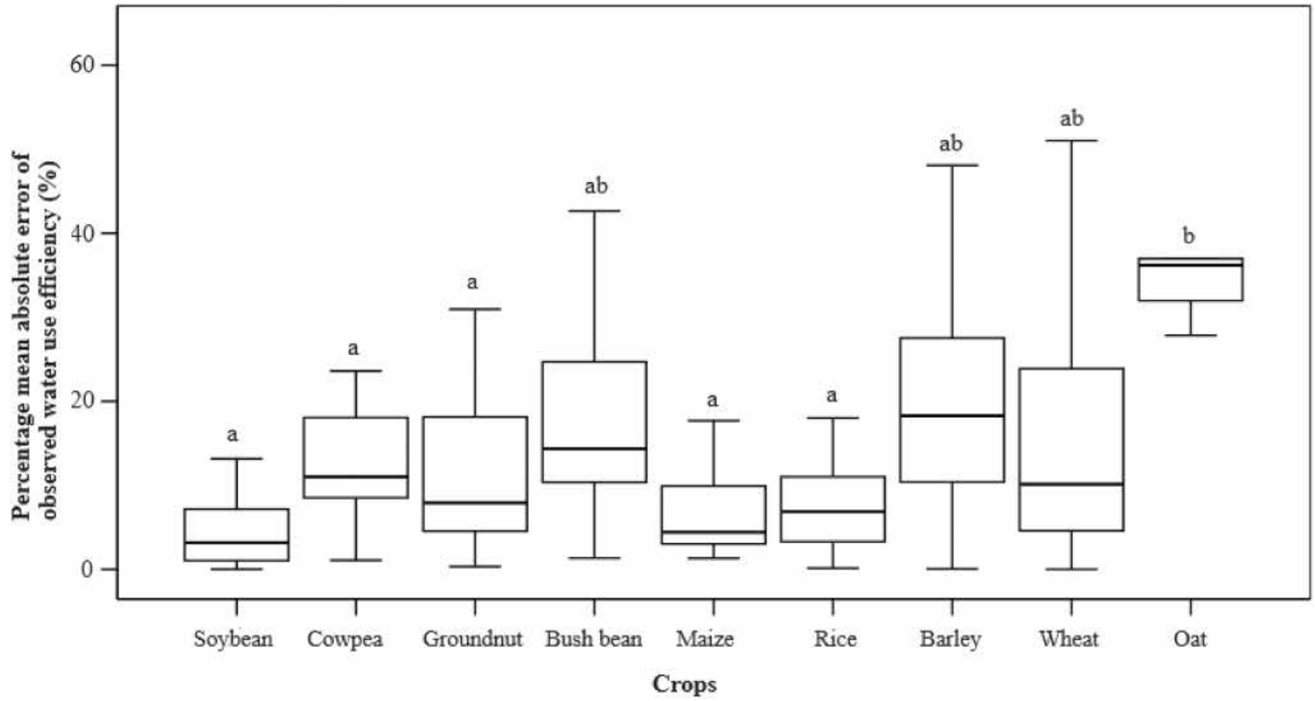

FIGURE 2 Boxplots comparing the percentage mean absolute errors of observed water use efficiency (%MAE) of using carbon isotope to estimate WUE in different crops. Each boxplot presents the minimum, maximum, median, quartile 1 (25%), and quartile 3 (75%) for percentage mean absolute errors of observed water use efficiency. Box plots accompanied by similar letters were not significantly different at $p < 0.05$.

than C_3 plants (Liu et al., 2022). The %MAE was higher on oat, and there was a significant difference between WUE_{obs} and WUE_{est}. This could be attributable to the ability of oats plants to grow better under low temperatures. Reportedly, low temperatures alter the transpiration rate and decrease photosynthetic rates leading to low carbon dioxide uptake (Paul et al., 2021). Hence, it can potentially affect the values of discrimination on Carbon-13.

Growing seasons or environmental conditions impact a lower %MAE in maize (1.3 ± 7.2%) and rice (1.2 ± 8.6%) than the %MAE of bush beans (1.8%19.9%), cowpea (2.3 ± 16.2%), and groundnuts (2.1 ± 14.3%). Overall, the results exhibited that the C_3 legume crops had a lower %MAE than C_3 cereal crops. This might be attributed to legume crops having a low rate of photo-respiration (Foyer et al., 2009) and they are grown on well-drained soils with adequate soil moisture and aeration, which could result in stable carbon isotope discrimination and affect the accuracy of WUE estimates.

4.2 | Impact of plant part samples estimating WUE using carbon isotopes

The sampled plant parts (e.g., grain, leaf, and aboveground biomass) have different carbon isotope compositions and led to variations in CID (Figure 3). The current findings agree with Zhao et al. (2004), who highlighted differences in CID values in leaf, grain, and aboveground biomass assays in wheat. The variation in the sampled plant parts' CID values can potentially affect the accuracy of WUE estimations. A combination of anatomical, physiological, and environmental factors (e.g., light intensity, temperature, and humidity) influence CID values and WUE estimation (Farquhar et al., 1989). Estimating WUE using grain CID appeared to be more accurate than other plant parts' CID, suggesting that measuring grain CID may require harvesting the crop at an appropriate or physiological stage of maturity (Pask, 2012; Pask & Reynolds, 2013). Grain CID values can accurately estimate WUE given the values are stable compared to values of the leaf and aboveground biomass samples. Also, Kondo et al. (2004) reported a similar trend in rice grain CID under different water regimes. There was a non-significant difference between the %MAE for grain and leaf CID values in estimating WUE. However, measuring WUE using leaf CID have a slightly higher %MAE than grain CID (Figure 3). This could be attributed to sampling at different growth stages (Laza et al., 2006), resulting in higher variations in carbon isotopic composition and high inaccuracy in WUE estimations. The use of leaf CID when estimating WUE is not ideal since leaf CID is strongly affected by environmental factors (e.g., light intensity and low temperatures) (Farquhar et al., 1989) and leaf age. Mature leaves can be sampled to measure CID and WUE estimation over a long period (Hussain

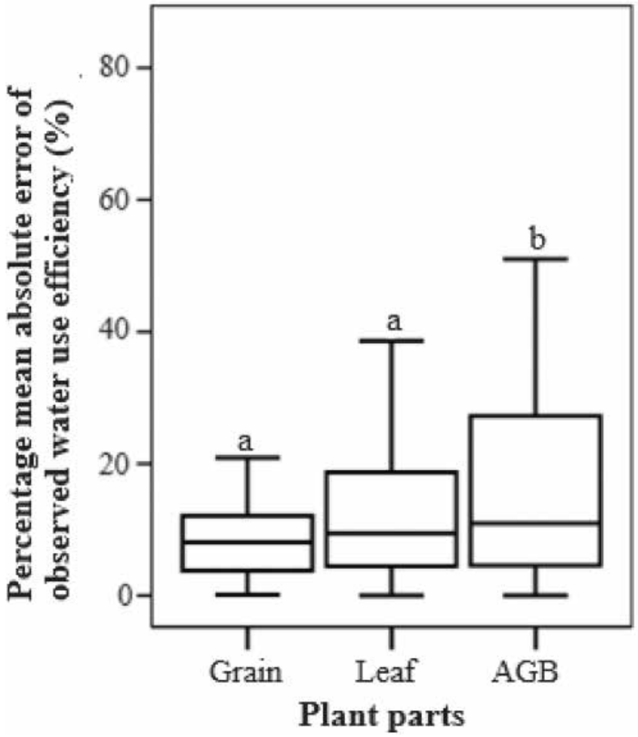

FIGURE 3 Boxplots comparing the percentage mean absolute errors (%MAE) of using carbon isotope discrimination from different plant parts in estimating WUE in plants. Each boxplot presents the minimum, maximum, median, quartile 1 (25%), and quartile 3 (75%) for percentage mean absolute errors of observed water use efficiency. Box plots accompanied by similar letters were not significantly different at $p < 0.05$. AGB, aboveground biomass.

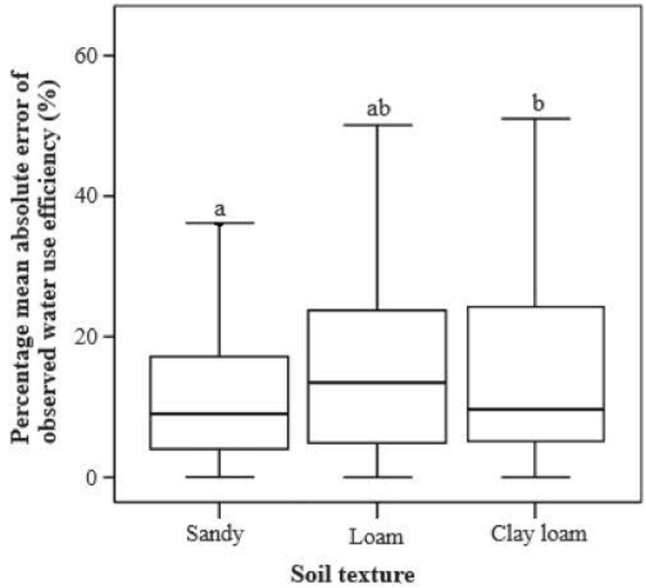

FIGURE 4 Boxplots comparing the percentage mean absolute error of observed water use efficiency (%MAE) of using carbon isotopes in estimating WUE in different soil textural classes. Each boxplot presents the minimum, maximum, median, quartile 1 (25%), and quartile 3 (75%) for percentage mean absolute errors of observed water use efficiency. Box plots accompanied by similar letters were not significantly different at $p < 0.05$.

et al., 2019). However, leaf aging or stress can influence CID values and could potentially lead to high %MAE. The use of aboveground biomass CID appeared to have an extremely high %MAE compared to leaf and grain CID. This is ascribed by the aboveground biomass CID is negatively affected by environmental conditions (Farquhar et al., 1989), which might not be directly related to WUE such as shading, nutrient availability and inter- and intra-plant competition which can cause noise in the isotopic ratio mass spectrometer (IRMS) and make the interpretation of aboveground biomass CID more complex leading to high level of inaccuracy of CID-based WUE estimations.

4.3 | Soil, climatic, and continental factors impacting the accuracy of using carbon isotopes in estimating WUE

4.3.1 | Soil texture

The use of carbon isotopes is a reliable and non-destructive technique for estimating WUE in crops. However, its accuracy varies depending on the texture of the soil. Yu et al. (2021) reported that soil texture affects the relationship between plant WUE and CID. The current analysis highlighted that soil texture has an impact when measuring WUE using CID, with the highest %MAE found on clay loam (2.8 ± 21.8%) than on sandy (1.3 ± 16.2%) and loam (1.1 ± 14%) soils (Figure 4). This could be attributable to clay loam soils having relatively low water infiltration rates and poor drainage, which can lead to waterlogging and reduced soil water availability. This impairs the crop's ability to extract water from the soil, reducing water use efficiency. In contrast, sand and loam soils have better drainage and higher infiltration rates, which facilitate water uptake by crops (Archer et al., 2020) and, in turn, improve CID-based WUE estimates. Coulouma et al. (2020) reported that the relationship between soil water and CID was significant under all environmental conditions. Wang et al. (2016) highlighted that CID decreases as the amount of soil water decreases. Conversely, the estimations in loam and sandy soils appeared to be more accurate, probably due to the large amount of root biomass in loam and sandy soils than in clay loam soil, rendering higher oxygen availability and mobilization (Silver et al., 2000). The higher root-to-shoot ratio allows for efficient water uptake and better CID, improving WUE estimates' accuracy.

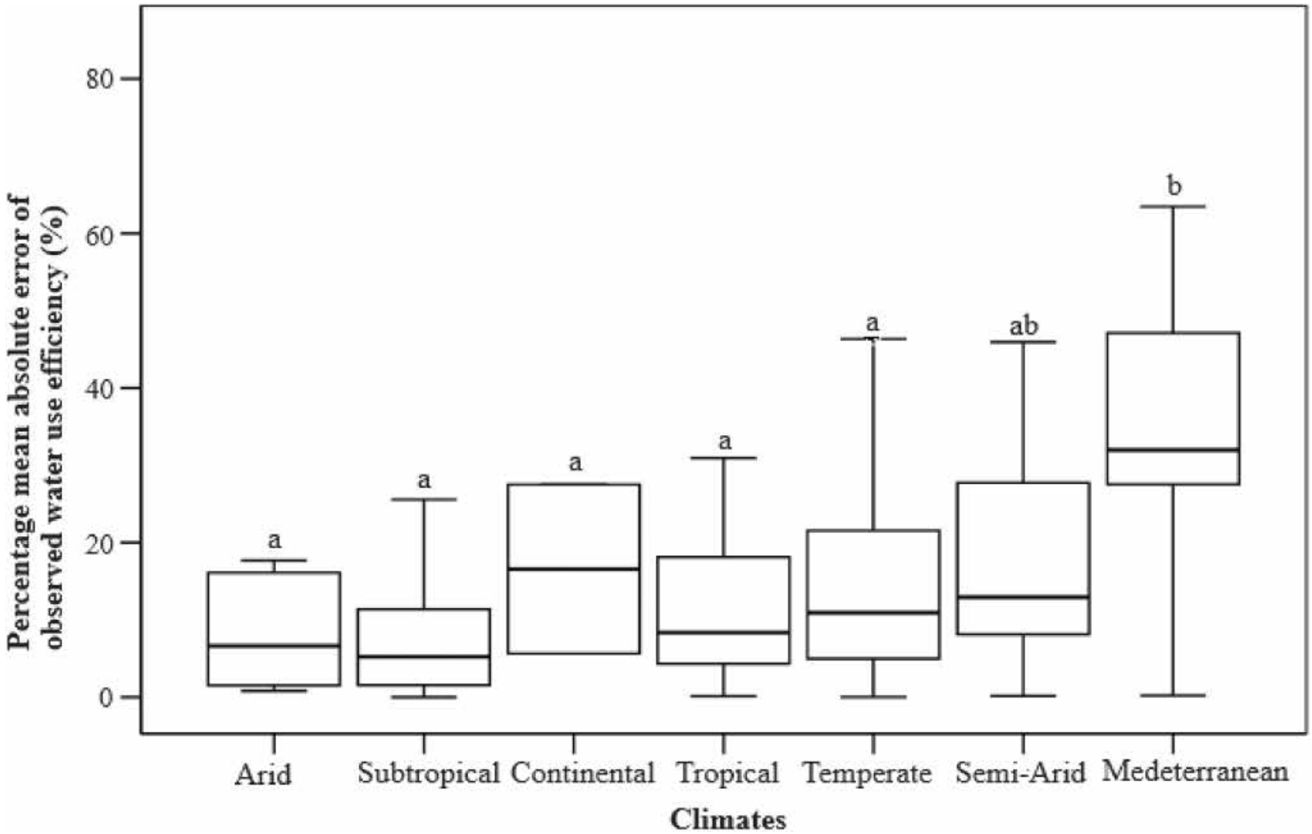

FIGURE 5 Boxplots comparing the percentage mean absolute errors of observed water use efficiency (%MAE) of using carbon isotopes in estimating WUE in different continents. Each boxplot presents the minimum, maximum, median, quartile 1 (25%), and quartile 3 (75%) for percentage mean absolute errors of observed water use efficiency. Box plots accompanied by similar letters were not significantly different at $p < 0.05$.

The use of carbon isotopes tends to either underestimate or overestimate WUE depending on the texture of the soil. In clay loam soils, carbon isotopes resulted in an overestimation of WUE given that clay loam soils render reduced root biomass coupled with lower oxygen availability and decreased nutrient supply (Cao et al., 2019). This might lead to a decrease in water uptake capacity and reduced plant growth, which may affect the accuracy of the CID-based WUE calculation. Therefore, lower biomass in roots increases CID and overestimates WUE. Furthermore, clay loam soil has a high-water holding capacity which can contribute to waterlogging and reduced soil water availability, leading to reduced WUE. However, in some cases, the high soil moisture content can also lead to increased CID (Kondo et al., 2004) and overestimated WUE. Contrarily, the use of CID underestimates computation of WUE of crop plants cultivated on loam soils, attributable to high soil nutrient availability leading to increased photosynthesis rates. An increased rate of photosynthesis helps the plant to discriminate better against ^{13}C (Nguyen-Thu et al., 2013), leading to an underestimation of WUE. Soil pH exhibited the lowest coefficient of variation, indicating a low contribution to the variation.

4.3.2 | Climate

The climates in the study areas were categorized based on MAP and MAT. The two climatic factors directly affect C_3 and C_4 plant growth, reproduction, and productivity. Among the climatic factors, temperatures can highly determine the level of accuracy when estimating crop WUE using carbon isotopes. Temperatures significantly impact the discrimination of carbon-13 in plants. The results highlighted that the %MAE differs with climates, with the Mediterranean climate having a higher %MAE than other climates (Figure 5). This could be because CID values vary from one climatic region to another (Rao & Wright, 1994; Schellenberg et al., 2010), and this can lead to variations and differences in the level of accuracy of using carbon isotopes to estimate WUE in different climates. Under different climatic zones, there are stark differences in evaporation rates, temperatures, and humidity. Koehler et al. (2010) reported that temperature levels differently affected the relationship between WUE and CID and impacted the accuracy level of water use efficiency estimates made using carbon isotopes.

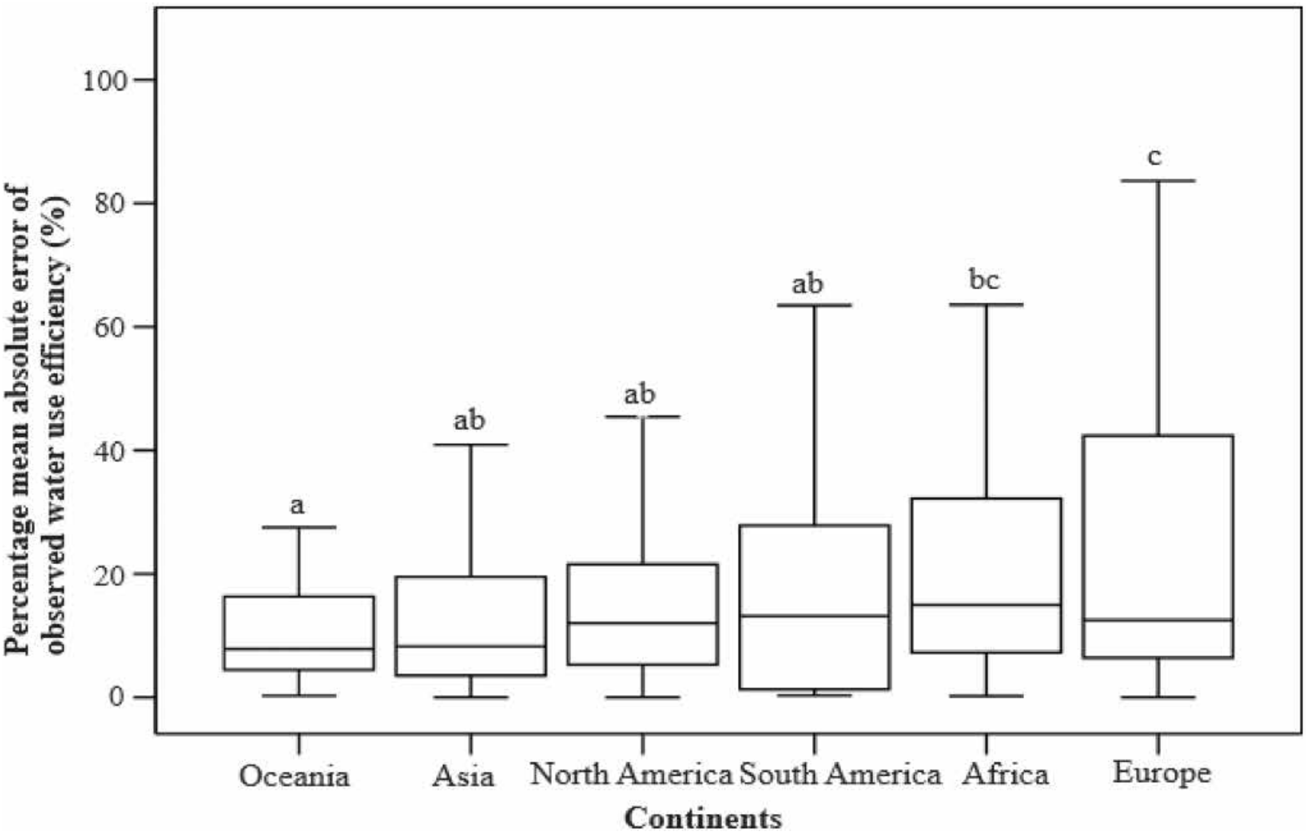

FIGURE 6 Boxplots comparing the percentage mean absolute errors (%MAE) of using carbon isotopes in estimating plant WUE in different climates. Each boxplot presents the minimum, maximum, median, quartile 1 (25%), and quartile 3 (75%) of percentage mean absolute errors of observed water use efficiency. Box plots accompanied by similar letters were not significantly different at $p < 0.05$.

Under the Mediterranean climate, the %MAE was higher than in any other climate included in this study. This is attributable to complex environmental factors such as temperature, light intensity, and atmospheric CO_2 concentrations are often highly variable in Mediterranean climates. This makes it more challenging to estimate plant WUE using the CID accurately. In addition, under the Mediterranean climate, rainfall is limited and unpredictable, leading to soil moisture variability, which causes stomata closure to conserve water under dry conditions, leading to higher leaves CID values (Khan et al., 2010). Conversely, stomata regularly open in wet conditions, leading to lower CID values. This fluctuation can affect the accuracy of the carbon isotope method. The present analysis recorded that the %MAE under continental climate had low variability than other climates. This could be possible because the temperatures under continental climates are not fluctuating.

The growing of C_3 cereals under all the climates resulted in non-significant differences in their %MAE. In comparison to WUE_{est} and WUE_{obs} under all climates, there was a non-significant difference between WUE_{est} and WUE_{obs} under all climates. The crop WUE computation obtained using direct and manual measurement and CID-based WUE estimations are both affected by temperatures. The %MAE was low under arid climatic conditions, given that under arid climatic conditions, plants tend to discriminate better against ^{13}C because the arid regions are characterized by low water availability, which tend to enhance carbon isotope discrimination in plants. Hence plants can have high WUE, and the CID method can accurately estimate the same. This agrees with Farquhar et al. (1989) who supported the assertion that arid climates can lead to higher WUE in crop plants and that CID is a reliable method for estimating water use efficiency.

Among the cereals assessed in the study, maize is a summer crop, and others (e.g., barley, wheat, rice, and oats) are C_3 winter crops. Variable temperatures in the summer and winter seasons cause differences in accuracy levels on summer and winter crops. The summer conditions might be more conducive for measuring WUE using isotopes, especially in the southern hemisphere, where summers are characterized by relatively higher temperatures, soil moisture, and more sunshine hours (Mbava et al., 2020). The winters in the Northern Hemisphere are generally cooler and drier with less sunshine, reducing carbon discrimination efficiency and leading to higher inaccuracy (Körner et al., 1991).

TABLE 5 Spearman's rank correlation coefficients between selected soil parameters and %MAE.

Variables	%MAE
CN	−0.08
CT	−0.11
Con	0.18**
BD	0.09
pH	0,08
Texture	0.11
Clay	0.09
Sand	0.30**
Silt	−0.40**
MAP	−0.11
Clim	0.05
MAT	−0.13
CID	0.12**
WUE_{obs}	−0.12**
WUE_{est}	−0.06

Abbreviations: %MAE, percentage mean absolute error of observed water use efficiency; %ME, percentage mean error of observed water use efficiency; BD, bulk density ($g\,cm^{-3}$); CID, carbon isotope discrimination (per thousands); Clim MAP, mean annual precipitation; CN, crop name; Con, continent; CT, crop type; MAT, mean annual temperature; ME, mean error; WUEest, estimated water use efficiency ($g\,L^{-1}$); WUEobs, water use efficiency ($g\,L^{-1}$).

**Correlations is significant at $p < 0.01$.

4.3.3 | The accuracy of estimating WUE using carbon isotopes in different continents

The present analysis highlighted that the environmental conditions in each continent impact the accuracy of using CID to estimate WUE. The inaccuracy level was higher in Europe than in other continents (Figure 6). That could be because the evaluations were only done in wheat (winter crop), and the winter temperatures in Europe are very low (Rimbu et al., 2014). Low temperatures highly affect carbon discrimination in plants, resulting in a reduced accuracy and underestimation of WUE (ME = −0.01) in Europe. The different environmental conditions in different continents strongly lead to the differences in the relationships between CID and WUE. That agrees with Arslan et al. (1999) and Zhao et al. (2009) who reported different correlations in wheat in Europe and Asia, respectively. Those differences in correlation relationship between CID and WUE fully suggest the differences in the level of inaccuracy from one continent to another.

The results showed that using CID to estimate WUE is more accurate in Asia than Europe, South America, North America, and Africa since the %MAE appeared lower in Asia (Figure 6). These results agree with Chen et al. (2011), who reported that CID in Asia provided a more accurate estimate of WUE than any other part of the world. Bren d'Amour et al. (2017) asserted that Asia has the world's largest and most diverse croplands, which have been subjected to intensive management practices for several decades. Agricultural practices in the region have greatly altered the natural carbon isotope ratios in the soil and plants, creating unique isotopic signatures that reflect the productivity and efficiency of these systems. In addition, the use of CID appears to be reliable in Asia due to the availability of well-calibrated isotopic standards (Laursen et al., 2016) and reference materials such as databases of regional and local carbon isotopic ratios. These databases are widely used to develop robust statistical models and algorithms that accurately estimate WUE from carbon isotope data. Furthermore, the present results indicated that there is a low variation of %MAE in Oceania (Figure 5). This could be because in Oceania, there are relatively stable climatic conditions, with consistent temperatures and rainfall patterns that can lead to low variations of the relationships between WUE and CID as well as low variations in %MAE.

4.4 | Association of factors contributing to the accuracy of carbon isotopes in estimating WUE

The degree of relationship between the factors contributing to the level of accuracy of using CID to estimate WUE guides the simultaneous use of the same in future programs. The positive correlations between %ME and %MAE under all environmental conditions (Table 5) suggest that crop types and environmental conditions with high %ME are more likely to have high %MAE. The %MAE is more linked to MAE, which was discerned by subtracting the WUE_{est} from $WUE_{obs.}$ The %ME should have been low values for reliable estimates and to reduce the %MAE given that both had a positive association in all the crops under all the environmental conditions. During the last two decades, plant breeders have been evaluating the correlations between WUE and CID in legumes and cereals (Akhter et al., 2010; Anyia et al., 2007; Impa et al., 2005; Javed et al., 2012).

The PCA-biplots (Figure 7) revealed that WUE_{obs}, MAT, and %ME were the major contributors to the variations in the level of inaccuracies (%MAE), which were strongly correlated with %MAE in crops, plant parts, and continents. The %ME was positively correlated with %MAE under all environmental factors and crops. The WUE_{obs} and MAT could increase or decrease accuracy (%MAE). MAT should be carefully considered when measuring WUE using carbon isotopes on all crop species and

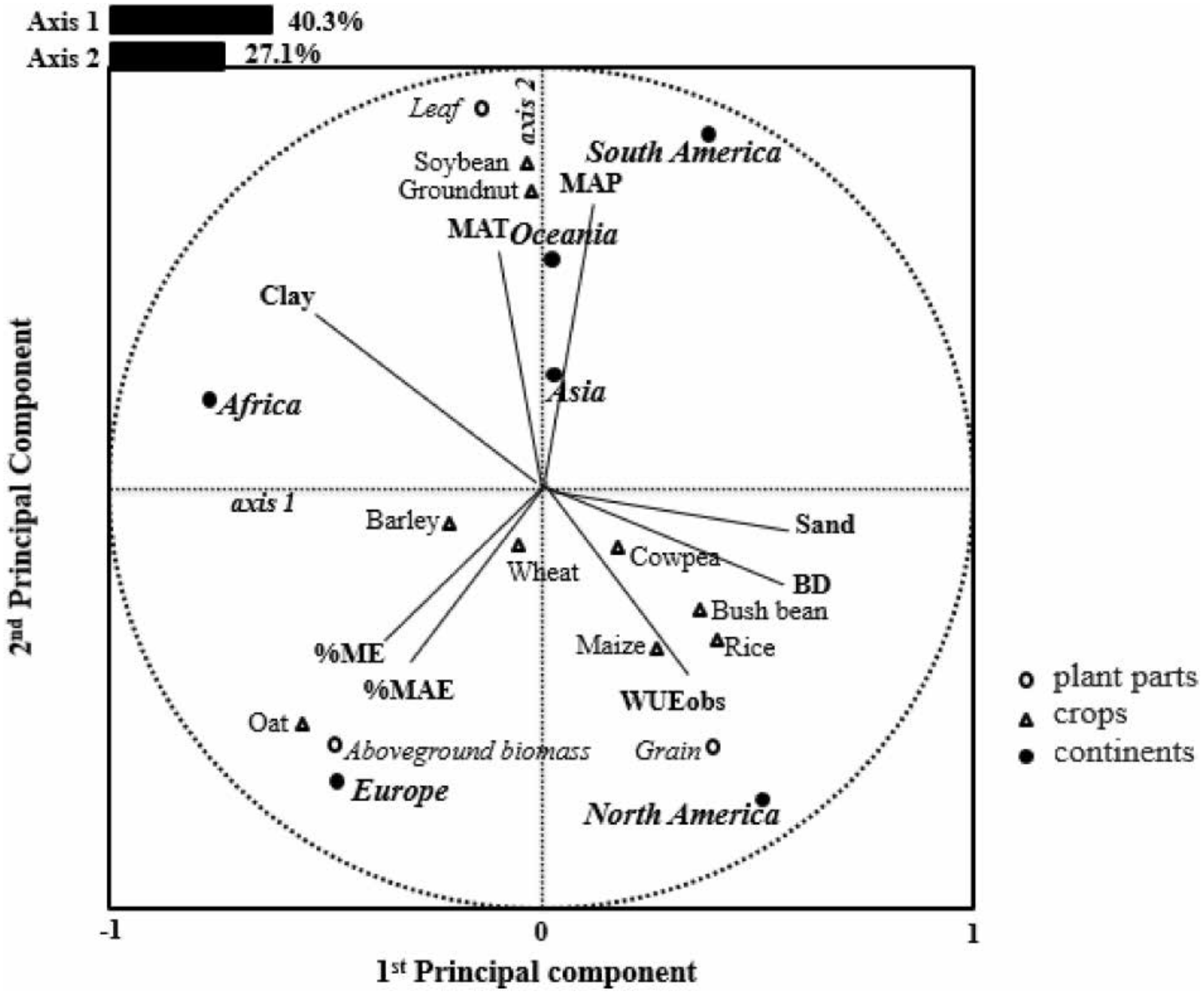

FIGURE 7 Principal component analyses (PCA) showing the relationship among environmental factors, soil properties, %ME, %MAE, $WUE_{obs,}$ crops, plant parts and continents. %MAE, percentage mean absolute error of observed water use efficiency; %ME, percentage mean error of observed water use efficiency; BD, soil bulk density ($g\,cm^{-3}$); MAP, mean annual precipitation; MAT, mean annual temperature; WUE_{obs}, observed water use efficiency ($g\,L^{-1}$).

soil properties. Low temperatures are associated with a decrease in CID (Zhou et al., 2011), and eventually, the %MAE increases. Conversely, high temperatures cause the plants to close their stomata, limiting the uptake of carbon dioxide (Smirnoff, 1993), consequently leading to increased ^{13}C: ^{12}C and %MAE.

5 | CONCLUSIONS

The study examined the impacts of soil, environmental conditions, and crop type on the accuracy of using carbon isotopes to estimate the WUE of cereal and legume crops. The conclusion drawn from 518 observations from 36 articles was that the level of accuracy depends on crop type, environmental factors, and soil properties. Legumes have significantly lower %MAE than cereal crops, suggesting that using carbon isotopes in estimating WUE involving more legume crops is highly reliable. Using CID to estimate WUE is more accurate for soybean, rice, and maize. The use of carbon isotopes to estimate WUE is limiting in oats because they appeared to have a high %MAE. The type of climate has an impact on the accuracy of using carbon isotopes to estimate WUE, with a high level of inaccuracy under Mediterranean climates. The CID-based WUE is underestimated in crops grown on loam soils. In Asia and Oceania, the measurement of WUE using isotopes is more accurate than in any other continent in the world. There is still a need to compare the accuracy of using CID on crop plants under the same climate conditions, soil properties, land management, and fertilizer regimes. The knowledge generated in this analysis is expected to be useful for choosing the crops, environmental factors, and soil properties that make the WUE estimation using carbon isotopes more accurate and dependable.

AUTHOR CONTRIBUTIONS

Maltase Mutanda: Conceptualization; draft preparation; data curation; formal analysis; investigation; methodology; resources; software; writing original draft; writing review and editing. Dr Vincent Chaplot: Conceptualization; funding acquisition; resources; supervision; validation; visualization; writing review and editing. Prof Hussein Shimelis: Conceptualization; data curation; funding acquisition; investigation; methodology; resources; validation; visualization; writing review and editing. Kwame W. Shamuyarira: Draft preparation; methodology; resources; validation; visualization; writing review and editing. Dr Sandiswa Figlan: Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; visualization; writing review and editing.

ACKNOWLEDGMENTS

This study was based on generous financial support from the Water Research Commission of the Republic of South Africa (WRC Project No. C2020/2021-00646). Thanks to the University of South Africa, the African Centre for Crop Improvement (ACCI-University of KwaZulu Natal), and the Institut de Recherche pour le Dévelopement (IRD-France) for the overall research support.

CONFLICT OF INTEREST STATEMENT

The authors have stated explicitly that there are no conflicts of interest in connection with this article.

DATA AVAILABILITY STATEMENT

Data will be made available on request.

ORCID

Maltase Mutanda https://orcid.org/0009-0008-3881-5834
Vincent Chaplot https://orcid.org/0000-0001-5430-362X
Hussein Shimelis https://orcid.org/0000-0003-2793-8392
Kwame W. Shamuyarira https://orcid.org/0000-0001-8016-159X
Sandiswa Figlan https://orcid.org/0000-0003-0395-8612

REFERENCES

Akhter, J., Monneveux, P., Sabir, S. A., Ashraf, M. Y., Lateef, Z., & Serraj, R. (2010). Selection of drought tolerant and high water use efficient rice cultivars through 13C isotope discrimination technique. *Pakistan Journal of Botany*, *42*(6), 3887–3897.

Akhter, J., Sabir, S. A., Atta, B. M., Ali, Y., & Lateef, Z. (2012). Carbon isotope discrimination as a selection tool for high yielding wheat genotypes for water limited environments. In International Atomic Energy Agency (Eds.), *Greater agronomic water use efficiency in wheat and rice using carbon isotope discrimination* (p. 105, 124). IAEA.

Anyia, A. O., Slaski, J. J., Nyachiro, J. M., Archambault, D. J., & Juskiw, P. (2007). Relationship of carbon isotope discrimination to water use efficiency and productivity of barley under field and greenhouse conditions. *Journal of Agronomy and Crop Science*, *193*(5), 313–323. https://doi.org/10.1111/j.1439-037X.2007.00274.x

Archer, N. A. L., Bell, R. A., Butcher, A. S., & Bricker, S. H. (2020). Infiltration efficiency and subsurface water processes of a sustainable drainage system and consequences to flood management. *Journal of Flood Risk Management*, *13*(3), e12629. https://doi.org/10.1111/jfr3.12629

Arslan, A., Zapata, F., & Kumarasinghe, K. S. (1999). Carbon isotope discrimination as indicator of water-use efficiency of spring wheat as affected by salinity and gypsum addition. *Communications in Soil Science and Plant Analysis*, *30*(19–20), 2681–2693. https://doi.org/10.1080/00103629909370405

Avramova, V., Meziane, A., Bauer, E., Blankenagel, S., Eggels, S., Gresset, S., Grill, E., Niculaes, C., Ouzunova, M., & Poppenberger, B. (2019). Carbon isotope composition, water use efficiency, and drought sensitivity are controlled by a common genomic segment in maize. *Theoretical and Applied Genetics*, *132*, 53–63. https://doi.org/10.1007/s00122-018-3193-4

Bren d'Amour, C., Reitsma, F., Baiocchi, G., Barthel, S., Güneralp, B., Erb, K.-H., Haberl, H., Creutzig, F., & Seto, K. C. (2017). Future urban land expansion and implications for global croplands. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(34), 8939–8944. https://doi.org/10.1073/pnas.1606036114

Briggs, L. J., & Shantz, H. L. (1913). The water requirement of plants. In J. E. Rockwell (Ed.), *Bureau of Plant Industry Bulletin Washington, DC* (pp. 282–285). US Department of Agriculture.

Brunel-Saldias, N., Seguel, O., Ovalle, C., Acevedo, E., & Martínez, I. (2018). Tillage effects on the soil water balance and the use of water by oats and wheat in a Mediterranean climate. *Soil and Tillage Research*, *184*, 68–77. https://doi.org/10.1016/j.still.2018.07.005

Cai, J. (1992). *Carbon isotope discrimination and water-use efficiency in field-grown wheat*. [Doctoral Dissertation, Oklahoma State University. 44 pages].

Cao, H., Ning, L., Xun, M., Feng, F., Li, P., Yue, S., Song, J., Zhang, W., & Yang, H. (2019). Biochar can increase nitrogen use efficiency of Malus hupehensis by modulating nitrate reduction of soil and root. *Applied Soil Ecology*, *135*, 25–32. https://doi.org/10.1016/j.apsoil.2018.11.002

Chen, J., Chang, S. X., & Anyia, A. O. (2011). The physiology and stability of leaf carbon isotope discrimination as a measure of water-use efficiency in barley on the Canadian prairies. *Journal of Agronomy and Crop Science*, *197*(1), 1–11. https://doi.org/10.1111/j.1439-037X.2010.00440.x

Coulouma, G., Prevot, L., & Lagacherie, P. (2020). Carbon isotope discrimination as a surrogate for soil available water capacity in rainfed areas: A study in the Languedoc vineyard plain. *Geoderma*, *362*, 114121. https://doi.org/10.1016/j.geoderma.2019.114121

da Silva, V. d. P., da Silva, B. B., Albuquerque, W. G., Borges, C. J., de Sousa, I. F., & Neto, J. D. (2013). Crop coefficient, water requirements, yield and water use efficiency of sugarcane growth in Brazil. *Agricultural Water Management*, *128*, 102–109. https://doi.org/10.1016/j.agwat.2013.06.007

Daryanto, S., Wang, L., & Jacinthe, P.-A. (2017). Global synthesis of drought effects on cereal, legume, tuber and root crops production: A review. *Agricultural Water Management*, *179*, 18–33. https://doi.org/10.1016/j.agwat.2016.04.022

Eggels, S., Blankenagel, S., Schön, C.-C., & Avramova, V. (2021). The carbon isotopic signature of C 4 crops and its applicability in breeding for climate resilience. *Theoretical and Applied Genetics*, *134*, 1663–1675. https://doi.org/10.1007/s00122-020-03761-3

Engoke, C., Chikoye, D., & Boahen, S. (2022). *Inoculant formulation and application determine nitrogen availability and water use efficiency in soybean production*. IntechOpen. https://doi.org/10.5772/intechopen.102639

Fang, Q. X., Ma, L., Green, T. R., Yu, Q., Wang, T. D., & Ahuja, L. R. (2010). Water resources and water use efficiency in the North China plain: Current status and agronomic management options. *Agricultural Water Management*, *97*(8), 1102–1116. https://doi.org/10.1016/j.agwat.2010.01.008

Farquhar, G. D., Ehleringer, J. R., & Hubick, K. T. (1989). Carbon isotope discrimination and photosynthesis. *Annual Review of Plant Biology*, *40*(1), 503–537. https://doi.org/10.1146/annurev.pp.40.060189.002443

Foyer, C. H., Bloom, A. J., Queval, G., & Noctor, G. (2009). Photorespiratory metabolism: Genes, mutants, energetics, and redox signaling. *Annual Review of Plant Biology*, *60*, 455–484. https://doi.org/10.1146/annurev.arplant.043008.091948

Guerrieri, R., Belmecheri, S., Ollinger, S. V., Asbjornsen, H., Jennings, K., Xiao, J., Stocker, B. D., Martin, M., Hollinger, D. Y., & Bracho-Garrillo, R. (2019). Disentangling the role of photosynthesis and stomatal conductance on rising forest water-use efficiency. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(34), 16909–16914. https://doi.org/10.1073/pnas.1905912116

Hafsi, M., Hadji, A., Semcheddine, N., Rouabhi, A., & Djekoun, A. (2009). *Selection for greater agronomic water use efficiency in wheat using carbon isotope discrimination in Algeria* (pp. 63–71). Sciences & Technologie. C, Biotechnologies.

Heng, L. K., Cai, G., Ramana, M. V., Sachdev, M. S., Rusan, M. M., Sijali, I. V., & Issaka, M. (2005). The effect of soil fertility, crop management on carbon-isotope discrimination and their relationships with yield and water-use efficiency of crops in semi-arid and arid environments. In International Atomic Energy Agency (Eds.), *Nutrient and water management practices for increasing crop production in rainfed arid/semi-arid areas, IAEA-TECDOC-1468* (pp. 15–41). IAEA.

Hoover, D. L., Abendroth, L. J., Browning, D. M., Saha, A., Snyder, K., Wagle, P., Witthaus, L., Baffaut, C., Biederman, J. A., Bosch, D. D., & Bracho, R. (2023). Indicators of water use efficiency across diverse agroecosystems and spatiotemporal scales. *Science of the Total Environment*, *864*, 160992. https://doi.org/10.1016/j.scitotenv.2022.160992

Huang, G., Zhang, X., Wang, Y., Feng, F., Mei, X., & Zhong, X. (2019). Comparisons of WUE in twelve genotypes of winter wheat and the relationship between delta (13)C and WUE. *PeerJ*, *7*, e6767. https://doi.org/10.7717/peerj.6767

Hussain, M. I., El-Keblawy, A., & Mitterand Tsombou, F. (2019). Leaf age, canopy position, and habitat affect the carbon isotope discrimination and water-use efficiency in three C3 leguminous *Prosopis* species from a hyper-arid climate. *Plants*, *8*(10), 402.

Impa, S. M., Nadaradjan, S., Boominathan, P., Shashidhar, G., Bindumadhava, H.-y., & Sheshshayee, M. S. (2005). Carbon isotope discrimination accurately reflects variability in WUE measured at a whole plant level in rice. *Crop Science*, *45*(6), 2517–2522. https://doi.org/10.2135/cropsci2005.0119

Ismail, A. M., & Hall, A. E. (1993). Inheritance of carbon isotope discrimination and water-use efficiency in cowpea. *Crop Science*, *33*(3), 498–503. https://doi.org/10.2135/cropsci1993.0011183x003300030016x

Javed, A., Ashraf, M. Y., Sabir, S. A., & Wajid, I. (2012). Use of carbon isotope discrimination technique to sustain rice productivity under stressed and low land irrigated ecosystem of Pakistan. *Pakistan Journal of Botany*, *44*(Suppl. 2), 85–93.

Jiang, Y., King, C. A., Purcell, L. C., & Wang, S. (2020). Nitrogen fixation sensitivity related to water use efficiency at reproductive development in soybean. *Plant, Soil and Environment*, *66*(7), 345–350. https://doi.org/10.17221/271/2020-pse

Kang, Y. K., Richards, R. A., & Condon, A. G. (1996). Interactions among carbon isotope discrimination, water use efficiency and nitrogen nutrition in wheat and barley. *The Korean Journal of Crop Science*, *41*(3), 318–331.

Khan, H. R., Paull, J. G., Siddique, K. H. M., & Stoddard, F. L. (2010). Faba bean breeding for drought-affected environments: A physiological and agronomic perspective. *Field Crops Research*, *115*(3), 279–286. https://doi.org/10.1016/j.fcr.2009.09.003

Khazaei, H., Mohammady, S.-D., Zaharieva, M., & Monneveux, P. (2008). Carbon isotope discrimination and water use efficiency in Iranian diploid, tetraploid and hexaploid wheats grown under well-watered conditions. *Genetic Resources and Crop Evolution*, *56*(1), 105–114. https://doi.org/10.1007/s10722-008-9349-3

Kirda, C., Mohamed, A., Kumarasinghe, K. S., Montenegro, A., & Zapata, F. (1992). Carbon isotope discrimination at vegetative stage as an indicator of yield and water use efficiency of spring wheat (*Triticum turgidum* L. var. durum). *Plant and Soil*, *147*, 217–223. https://doi.org/10.1007/bf00029073

Knight, J. D., Livingston, N. J., & Kessel, C. (1994). Carbon isotope discrimination and water-use efficiency of six crops grown under wet and dryland conditions. *Plant, Cell and Environment*, *17*(2), 173–179. https://doi.org/10.1111/j.1365-3040.1994.tb00280.x

Koehler, I. H., Poulton, P. R., Auerswald, K., & Schnyder, H. (2010). Intrinsic water-use efficiency of temperate seminatural grassland has increased since 1857: An analysis of carbon isotope discrimination of herbage from the park grass experiment. *Global Change Biology*, *16*(5), 1531–1541. https://doi.org/10.1111/j.1365-2486.2009.02067.x

Kondo, M., Pablico, P., Aragones, D., & Agbisit, R. (2004). Genotypic variations in carbon isotope discrimination, transpiration efficiency, and biomass production in rice as affected by soil water conditions and N. *Plant and Soil*, *267*, 165–177. https://doi.org/10.1007/s11104-005-4884-6

Köppen, W. (1936). Das geographisca System der Klimate. In W. Köppen, & G. Geiger (Eds.), *Handbuch der Klimatologie* (pp. 1–44). C. Gebr, Borntraeger.

Körner, C., Farquhar, G. D., & Wong, S. C. (1991). Carbon isotope discrimination by plants follows latitudinal and altitudinal trends. *Oecologia*, *88*, 30–40. https://doi.org/10.1007/bf00328400

Kugedera, A. T., Mandumbu, R., & Nyamadzawo, G. (2022). Rainwater harvesting and *Leucaena leucocephala* biomass rates effects on soil moisture, water use efficiency and *Sorghum bicolor* [(L.) moench] productivity in a semi-arid area in Zimbabwe. *Journal of the Science of Food and Agriculture*, *102*(14), 6443–6453. https://doi.org/10.1002/jsfa.12011

Laursen, K. H., Bontempo, L., Camin, F., & Rossmann, A. (2016). Advances in isotopic analysis for food authenticity testing. In Woodhead Publishing (Eds.), *Advances in food authenticity testing* (pp. 227–252). Elsevier. https://doi.org/10.1016/B978-0-08-100220-9.00009-6

Laza, M. R., Kondo, M., Ideta, O., Barlaan, E., & Imbe, T. (2006). Identification of quantitative trait loci for δ13C and productivity in irrigated lowland rice. *Crop Science*, *46*(2), 763–773. https://doi.org/10.2135/cropsci2005.05.0084

Liu, S. (2016). *Contributions of within-population trait variation to Brachypodium hybridum invasions in California and of population-based functional traits to germination patterns in a guild of desert plants*. University of California.

Liu, W.-J., Liu, H., Chen, Y.-E., Yin, Y., Zhang, Z.-W., Song, J., Chang, L.-J., Zhang, F.-L., Wang, D., & Dai, X.-H. (2022). Chloroplastic photoprotective strategies differ between bundle sheath and mesophyll cells in maize (*Zea mays* L.) under drought. *Frontiers in Plant Science*, *13*, 885781. https://doi.org/10.3389/fpls.2022.885781

Liu, Z., Ma, F.-y., Hu, T.-x., Zhao, K.-g., Gao, T.-p., Zhao, H.-x., & Ning, T.-y. (2020). Using stable isotopes to quantify water uptake from different soil layers and water use efficiency of wheat under long-term tillage and straw return practices. *Agricultural Water Management*, *229*, 105933. https://doi.org/10.1016/j.agwat.2019.105933

López-Castañeda, C., & Richards, R. A. (1994). Variation in temperate cereals in rainfed environments III. Water use and water-use efficiency. *Field Crops Research*, *39*(2–3), 85–98. https://doi.org/10.1016/0378-4290(94)90011-6

Ma, Q. J., Zhang, Q., Niu, J., & Li, X. G. (2020). Plastic-film mulch cropping increases mineral-associated organic carbon accumulation in maize cropped soils as revealed by natural 13C/12C ratio signature. *Geoderma*, *370*, 114350. https://doi.org/10.1016/j.geoderma.2020.114350

Martínez, J., & Reca, J. (2014). Water use efficiency of surface drip irrigation versus an alternative subsurface drip irrigation method. *Journal of Irrigation and Drainage Engineering*, *140*(10), 04014030. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000745

Mbava, N., Mutema, M., Zengeni, R., Shimelis, H., & Chaplot, V. (2020). Factors affecting crop water use efficiency: A worldwide meta-analysis. *Agricultural Water Management*, *228*, 105878. https://doi.org/10.1016/j.agwat.2019.105878

Meißner, A. (2021). *Water use efficiency of arable and grassland crops in legume-based intercropping systems* (Vol. *4*). Cuvillier Verlag.

Nadaradjan, S., Impa, S. M., Parsi, S. G., Sheshshayee, M. S., Udayakumar, M., & Prasad, T. G. (2005). Overlapping markers for WUE and carbon isotope discrimination in doubled haploid population of Rice. *Journal Of Plant Biology*, *32*(2), 117–124.

Nguyen-Thu, H., Drevet, J. R., & Escoute, J. (2013). Carbon isotopic fractionation and discrimination in C3-crops: How does it relate to improved water use efficiency? *Photosynthesis Research*, *117*(1–2), 243–258.

Parmoon, G., Ebadi, A., Hashemi, M., Hawrylak-Nowak, B., Baskin, C., & Jahanbakhsh, S. (2022). Plant growth regulators improve grain production and water use efficiency of *Foeniculum vulgare* mill. Under water stress. *Plants*, *11*(13), 1718.

Parniske, M. (2018). Uptake of bacteria into living plant cells, the unifying and distinct feature of the nitrogen-fixing root nodule symbiosis. *Current Opinion in Plant Biology*, *44*, 164–174.

Pask, A. (Ed.). (2012). *Physiological breeding: A field guide to wheat phenotyping. II*. The International Maize and Wheat Improvement Center.

Pask, A., & Reynolds, M. (2013). Breeding for yield potential has increased deep soil water extraction capacity in irrigated wheat. *Crop Science*, *53*(5), 2090–2104.

Paul, S., Bera, S., Dasgupta, R., Mondal, S., & Roy, S. (2021). Review on the recent structural advances in open and closed systems for carbon capture through algae. *Energy Nexus*, *4*, 100032.

Pronger, J., Campbell, D. I., Clearwater, M. J., Mudge, P. L., Rutledge, S., Wall, A. M., & Schipper, L. A. (2019). Toward optimisation of water use efficiency in dryland pastures using carbon isotope discrimination as a tool to select plant species mixtures. *Science of the Total Environment*, *665*, 698–708.

Raeini-Sarjaz, M., Barthakur, N. N., Arnold, N. P., & Jones, P. J. H. (1998). Water stress, water use efficiency, carbon isotope discrimination and leaf gas exchange relationships of the bush bean. *Journal of Agronomy and Crop Science*, *180*(3), 173–179.

Raeini-Sarjaz, M., & Chalavi, V. (2008). Effects of diverse microclimates and soil water contents on water-use efficiency and carbon isotope discrimination for bush bean. *Journal of Agricultural Science and Technology*, *10*(1), 43–53.

Rao, R. N., Williams, J. H., Wadia, K. D. R., Hubick, K. T., & Farquhar, G. D. (1993). Crop growth, water-use efficiency and carbon isotope discrimination in groundnut (*Arachis hypogaea* L.) genotypes under end-of season drought conditions. *Annals of Applied Biology*, *122*(2), 357–367.

Rao, R. N., & Wright, G. (1994). Stability of the relationship between specific leaf area and carbon isotope discrimination across environments in peanut. *Crop Science*, *34*(1), 98–103.

Rimbu, N., Lohmann, G., & Ionita, M. (2014). Interannual to multidecadal Euro-Atlantic blocking variability during winter and its relationship with extreme low temperatures in Europe. *Journal of Geophysical Research: Atmospheres*, *119*(24), 13–621.

Santesteban, L. G., Miranda, C., Barbarin, I., & Royo, J. B. (2015). Application of the measurement of the natural abundance of stable isotopes in viticulture: A review. *Australian Journal of Grape and Wine Research*, *21*(2), 157–167.

Schellenberg, A., Chmielus, S., Schlicht, C., Camin, F., Perini, M., Bontempo, L., Heinrich, K., Kelly, S. D., Rossmann, A., & Thomas, F. (2010). Multielement stable isotope ratios (H, C, N, S) of honey from different European regions. *Food Chemistry*, *121*(3), 770–777.

Shaheen, R., & Hood-Nowotny, R. C. (2005). Effect of drought and salinity on carbon isotope discrimination in wheat cultivars. *Plant Science*, *168*(4), 901–909. https://doi.org/10.1016/j.plantsci.2004.11.003

Shan, N., Zhang, Y., Chen, J. M., Ju, W., Migliavacca, M., Peñuelas, J., Yang, X., Zhang, Z., Nelson, J. A., & Goulas, Y. (2021). A model for estimating transpiration from remotely sensed solar-induced chlorophyll fluorescence. *Remote Sensing of Environment*, *252*, 112134.

Silver, W. L., Neff, J., McGroddy, M., Veldkamp, E., Keller, M., & Cosme, R. (2000). Effects of soil texture on belowground carbon and nutrient storage in a lowland Amazonian forest ecosystem. *Ecosystems*, *3*, 193–209.

Smirnoff, N. (1993). Tansley review No. 52. The role of active oxygen in the response of plants to water deficit and desiccation. *New Phytologist*, *125*, 27–58.

Thameur, A., Lachiheb, B., & Ferchichi, A. (2018). Carbon isotope discrimination and gas exchange parameters impairment under drought conditions in five barley (*Hordeum vulgare* L.) genotypes. *Journal of New Sciences*, *50*, 3082–3093.

Tobita, S., Yamanaka, N., Nepomuceno, A. L., Farias, J. R. B., Neumaier, N., Senoo, S., & Nastasa, V. (2007). Physiological evaluation of drought tolerance in Brazilian soybean cultivars: water use efficiency and carbon isotope discrimination.

Wang, Y., Zhang, X., Zhang, X., Shao, L., Chen, S., & Liu, X. (2016). Soil water regime affecting correlation of carbon isotope discrimination with yield and water-use efficiency of winter wheat. *Crop Science*, *56*(2), 760–772. https://doi.org/10.2135/cropsci2014.11.0793

White, D. S., Bell, M. J., & Wright, G. C. (1996). The potential to use carbon isotope discrimination as a selection tool to improve water use efficiency in soybean. In *Proceedings of the 8th Australian agronomy conference, Toowoomba, QLD* (Vol. *728*). The Regional Institute Online Publishing.

Wright, G. C., & Rao, R. C. N. (1993). *Carbon isotope discrimination, water-use efficiency, specific leaf area relationships in groundnut*.

Wright, G. C., Rao, R. C. N., & Farquhar, G. D. (1994). Water-use efficiency and carbon isotope discrimination in peanut under water deficit conditions. *Crop Science*, *34*(1), 92–97. https://doi.org/10.2135/cropsci1994.0011183X003400010016x

Yang, W., & Li, P.-F. (2018). Association of carbon isotope discrimination with leaf gas exchange and water use efficiency in maize following soil amendment with superabsorbent hydrogel. *Plant, Soil and Environment*, *64*(10), 484–490.

Yin, X., Sun, Z., Struik, P. C., Van der Putten, P. E. L., Van Ieperen, W. I. M., & Harbinson, J. (2011). Using a biochemical C4 photosynthesis model and combined gas exchange and chlorophyll fluorescence measurements to estimate bundle-sheath conductance of maize leaves differing in age and nitrogen content. *Plant, Cell & Environment*, *34*(12), 2183–2199.

Yin, Z.-H., & Raven, J. A. (1998). Influences of different nitrogen sources on nitrogen-and water-use efficiency and carbon isotope discrimination in C 3 *Triticum aestivum* L. and C 4 *Zea mays* L. plants. *Planta*, *205*, 574–580.

Yu, R., Zaccaria, D., Kisekka, I., & Kurtural, S. K. (2021). Soil apparent electrical conductivity and must carbon isotope ratio provide indication of plant water status in wine grape vineyards. *Precision Agriculture*, *22*(4), 1333–1352.

Zhang, B., Liu, W., Chang, S. X., & Anyia, A. O. (2010). Water-deficit and high temperature affected water use efficiency and arabinoxylan concentration in spring wheat. *Journal of Cereal Science*, *52*(2), 263–269.

Zhang, C., Zhang, J., Zhang, H., Zhao, J., Wu, Q., Zhao, Z., & Cai, T. (2015). Mechanisms for the relationships between water-use efficiency and carbon isotope composition and specific leaf area of maize (*Zea mays* L.) under water stress. *Plant Growth Regulation*, *77*(2), 233–243. https://doi.org/10.1007/s10725-015-0056-8

Zhang, H., Han, K., Gu, S., & Wang, D. (2019). Effects of supplemental irrigation on the accumulation, distribution and transportation of 13C-photosynthate, yield and water use efficiency of winter wheat. *Agricultural Water Management*, *214*, 1–8. https://doi.org/10.1016/j.agwat.2018.12.028

Zhao, B., Kondo, M., Maeda, M., Ozaki, Y., & Zhang, J. (2004). Water-use efficiency and carbon isotope discrimination in two cultivars of upland rice during different developmental stages under three water regimes. *Plant and Soil*, *261*, 61–75.

Zhao, H., Zhao, Z., An, L., Chen, T., Wang, X., & Feng, H. (2009). The effects of enhanced ultraviolet-B radiation and soil drought on water use efficiency of spring wheat. *Journal of Photochemistry and Photobiology B: Biology*, *94*(1), 54–58. https://doi.org/10.1016/j.jphotobiol.2008.09.005

Zheng, S., Cui, N., Gong, D., Wang, Y., Hu, X., Feng, Y., & Zhang, Y. (2020). Relationship between stable carbon isotope discrimination and water use efficiency under deficit drip irrigation of kiwifruit in the humid areas of South China. *Agricultural Water Management*, *240*, 106300.

Zhou, Y., Fan, J., Zhang, W., Harris, W., Zhong, H., Hu, Z., & Song, L. (2011). Factors influencing altitudinal patterns of C 3 plant foliar carbon isotope composition of grasslands on the Qinghai-Tibet plateau, China. *Alpine Botany*, *121*, 79–90.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Mutanda, M., Chaplot, V., Shimelis, H., Shamuyarira, K. W., & Figlan, S. (2024). Determinants of the accuracy of using carbon isotopes in estimating water use efficiency of selected cereal and legume crops: A global perspective. *Food and Energy Security*, *13*, e522. https://doi.org/10.1002/fes3.522