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Connecting the water footprint with the water-energy-food-ecosystems nexus concept and its added value in the Mediterranean

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A B S T R A C T

The Mediterranean region faces significant challenges within the Water-Energy-Food-Ecosystem (WEFE) Nexus due to water scarcity, increasing agricultural and energy demands, and ecosystem degradation exacerbated by climate change. This research addresses these challenges by integrating two water footprint (WF) methodologies, the volumetric Water Footprint Assessment (WFA) and the impact-oriented Water Scarcity Footprint (WSF) and then correlating the results with the WEF Nexus Index and other sustainability indicators, to explore trade-offs and synergies across water, energy, food, and ecosystem dimensions at multiple scales. Findings highlight that the most significant impacts of water consumption stem from the cultivation of water-intensive crops in water-scarce regions, both within and beyond the Mediterranean. This underscores the pivotal role of virtual water trade and the global implications of local water management practices. The results further reveal critical disparities in water resource use and stress among Mediterranean countries, emphasizing the need for targeted policy interventions and international cooperation to address these challenges. By elucidating the interdependencies between water and the other WEFE Nexus dimensions, this study contributes valuable insights for policymakers, researchers, and stakeholders striving to achieve sustainable resource management and resilience in the Mediterranean region and beyond.

1. Introduction

The Mediterranean region faces significant challenges at the intersection of water, energy, food, and ecosystems, commonly referred to as the Water-Energy-Food-Ecosystem (WEFE) nexus (Lucca et al., 2023). Scarcity and uneven distribution of water resources, coupled with increasing demand from agriculture, urbanization, and industry, present significant stressors (Leduc et al., 2017; Segurado et al., 2018). Agriculture, which is heavily reliant on water, drives over-extraction of groundwater, leading to issues such as salinization and degradation of soils (Mulligan et al., 2016). As pointed out by Antonelli et al. (2022), the agri-food system of the south of the region will have to face increasing pressures on water resources, vulnerability to climate change and nutritional challenges. This will be accompanied by a larger consumption of fertilisers and use of energy required for water pumping and desalination, linking the water and energy demands tightly together (Maftouh et al., 2022). In addition, the region's ecosystems, which host significant biodiversity, face degradation due to unsustainable practices and land-use changes (Malek et al., 2018; Ferreira et al., 2022).

Climate change exacerbates these issues, leading to more frequent droughts and altering precipitation patterns, further straining the water supply (Tramblay et al., 2020). Indeed, climate models consistently project that the Mediterranean Basin will experience regional warming at rates about 20% higher than global averages and a 12% reduction in rainfall with 3 °C of global warming (IPCC, 2023).

Addressing these intertwined challenges requires an integrated approach that considers the interdependencies within the WEFE nexus to promote sustainability and resilience in the Mediterranean (Malagó et al., 2021). As water availability remains a key constraint to meeting the growing food and energy demands of an increasingly affluent global

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population (D'Odorico et al., 2018), the water footprint (WF) concept can provide useful information to address the Nexus (Vanham, 2016; Daccache et al., 2014; Lacirignola et al., 2014).

Indeed, by quantifying the amount of water used in producing goods and services, the WF can reveal the intricate connections between water use and energy production, as well as agricultural activities thus providing insights into the trade-offs and synergies between the Nexus dimensions. The WF can be categorized into two main types, depending on the assessment procedure: the "quantitative" water footprint and the "qualitative-oriented" water footprint. The former (Hoekstra and Mekonnen, 2012) focuses on the volumetric assessment of water use (WFA). In contrast, the latter, also known as the life cycle assessment (LCA) water footprint, aims to assess both qualitative and quantitative impacts of water use (Berger and Finkbeiner, 2013; Wu et al., 2022).

While the WFA emerged under the auspices of Integrated Water Resources Management (IWRM), the LCA-WF has undergone significant evolution within the broader LCA community, culminating in the establishment of a dedicated ISO standard, ISO 14046, in 2014.

Despite their differences, opportunities exist for synergy between the two methodologies. For instance, the green water consumption included in the WFA framework is relevant for water management but not yet accounted for in LCA methodology, while the WFA could leverage LCA-WF impact assessment methodologies to better assess the sustainability of freshwater use.

Several authors have compared both methodologies (Pacetti et al., 2015; Boulay et al., 2013; Berger and Finkbeiner, 2010) and applied them to different food products, to assess the advantages and disadvantages of each one. However, most research relies on either volumetric assessment of water use or impact-oriented approaches, with limited exploration of how these methodologies can complement each other to provide a more comprehensive understanding of water resource management (Gerbens-Leenes et al., 2021) and its role within the Nexus. Furthermore, it is crucial to consider the global implications of the WEFE Nexus (Endo et al., 2017), for example including the implications of virtual water trade and the environmental impacts of importing water-intensive goods (Mekonnen et al., 2024), which many studies often overlook.

This paper addresses these gaps by combining the WFA and WSF methodologies within the WEFE Nexus framework. This integration provides a novel approach to understanding the dynamics of water use and scarcity across the Mediterranean region and beyond. By correlating the results of these methodologies with the WEF Nexus Index and other sustainability indicators, the study offers fresh insights into the interdependencies among water, energy, food, and ecosystems at multiple scales.

This research contributes to a more holistic understanding of water resource management in the Mediterranean. It provides actionable insights for policymakers, researchers, and stakeholders striving to balance water, food, energy, and ecosystem security in a region characterized by its complex environmental, economic, and social dynamics.

2. Methodology

This study is based on the integration of the two main water footprint (WF) assessment approaches presented in the introduction with the WEFE nexus (Fig. 1). In addition to the national blue WF and WSF, this study covers WF and WSF of agriculture, including virtual water trade. The following paragraph further contrasts WF and WSF.

The water footprint (WF) measures the total volume of water consumed or polluted during production, categorized into blue (surface and groundwater), green (rainwater), and grey (pollution-assimilation) components, without considering local water availability or scarcity (Hoekstra and Mekonnen, 2012). In contrast, the water scarcity footprint (WSF) contextualizes water use by accounting for the scarcity of water resources in a specific region, using characterization factors to evaluate the environmental impact of water consumption (Boulay et al., 2018). While the WF focuses on quantifying water use, the WSF provides a scarcity-weighted assessment of the blue (fresh-) water component of the WF, making it more effective in identifying sustainability challenges in water-stressed areas. As shown in Fig. 1, a (simple) version of a WSF of an activity or organization is obtained by multiplying the blue water footprint of that activity or organization with a characterization factor. Commonly, however, WSFs can at the same time cover water consumption in different locations and to different seasons of the year, all with varying characterization factors, which makes their calculations more complex. This is out of the scope of this paper.

The methodology section is divided into four parts. The first part (section 2.1) presents the data sources used in this study. Sections 2.2 and 2.3 explain how WSF and WF are calculated and section 2.4 details the comparison of the WF and WSF results with the WEFE nexus indicators. With the WSF, the environmental impact of blue water consumption is evaluated at different levels of detail and scale (from the single agricultural sector up to the national level and beyond including

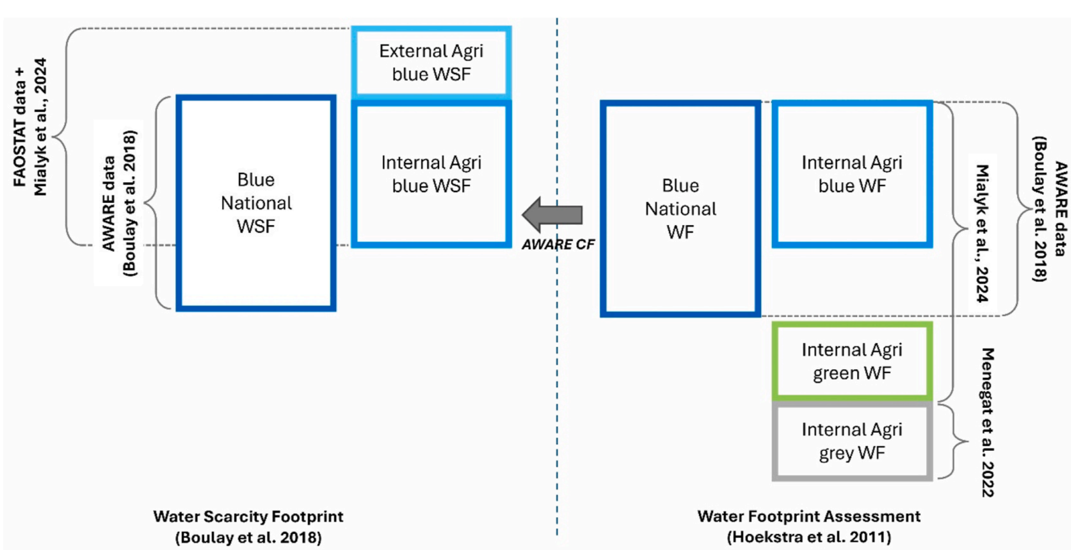

Fig. 1. Different types of water footprints considered in the study.

the country external WSF for agricultural products). With the methodology by Hoekstra et al. (2011), the WFA is applied to the national level, focusing on blue water footprints. Additionally, the agricultural water consumption is assessed with its blue, green and grey WF, providing a comprehensive assessment of the agricultural impact on water resources in each country. Finally, the results obtained with the two approaches are analyzed in terms of their correlation with other Nexus related variables to evaluate their effectiveness in providing useful information to characterize the Nexus and its structure in the Mediterranean.

2.1. Data sources

To comprehensively analyse the integration of the WF and WSF with the WEFE Nexus in the Mediterranean, this study utilizes a diverse set of datasets (also depicted in Fig. 1). These datasets provide the foundation for the WF and WSF calculations, as well as for correlation analyses with Nexus-related variables. Below, we describe the key data sources used in the study. Note that Supplementary Information S1 provides all data used and the corresponding references.

2.1.1. National water consumption and scarcity data

- National-level water consumption data were sourced from input data of the AWARE method, a globally recognized method for assessing water scarcity impacts in LCA. Input data of the latest version, AWARE2.0 (Seitfudem et al., 2024, currently in review), was employed alongside input data of the previous version (Boulay et al., 2018) to enhance the results' robustness. The data results from global hydrological modeling, which limits its accuracy compared to annual national statistics. However, the data quality is estimated to be sufficient for the purpose of this study. Furthermore, non-marginal AWARE characterization factors were retrieved from Boulay et al. (2020).
- Population data for the calculation of per capita WSFs were retrieved from the FAO AQUASTAT database (FAO, 2021), which provides comprehensive global water statistics.

2.1.2. Agricultural water footprints

- Mialyk et al. (2024) Dataset: Annual irrigation water consumption for key Mediterranean crops, including wheat, olives, barley, rice, maize, fodder, cotton, and dates, was sourced from the study by Mialyk et al. (2024). This dataset provides consistent temporal coverage (2010–2019) and geographical specificity, ensuring alignment with the study's objectives.
- FAOSTAT Trade Matrix: To assess the water footprints of imported crops, data on raw product imports in metric tons were extracted from the FAOSTAT database. This allowed for comparative analyses of domestic versus imported crop impacts.

2.1.3. Environmental and economic indicators

- Environmental Performance Index (EPI): To evaluate the environmental dimension of the WEFE Nexus, the study incorporated data from the EPI (Wolf et al., 2022), which includes metrics on ecosystem vitality, water resources, and climate change mitigation.
- Water-Energy-Food (WEF) Nexus Index: Developed by Simpson et al. (2022), this index aggregates water, energy, and food access and availability indicators. It was used to establish correlations with the WF and WSF results, providing insights into the systemic impacts of water use.

2.1.4. Supplementary calculations

- Nitrogen Load Data: For the grey WF calculation, nitrogen application rates, crop nitrogen uptake, and potential leaching data were derived from the study by Menegat et al. (2022). These inputs were critical for assessing the volume of freshwater required to assimilate agricultural pollutants.

By integrating these diverse data sources, the study ensures a holistic assessment of water use and its implications within the WEFE Nexus framework. Detailed descriptions of dataset mappings, methodologies, and assumptions are available in Supplementary Information 1 and 2.

2.2. Water scarcity footprint

The Available Water Remaining (AWARE) method (Boulay et al., 2018) quantifies the available water remaining per watershed area once the demand of humans and aquatic ecosystems has been met (Eq. (1)), set into relation to a global average (Eq. (2)). This indicator value (also called "characterization factor") serves as a proxy for the potential impact of water consumption on other water users in a certain watershed and month. The use as a proxy is justified by the "assumption that the potential to deprive another user of water is directly proportional to the amount of water consumed and inversely proportional to the available water remaining per unit of surface and time in a region" (Boulay et al., 2018). To determine the potential impact (the WSF) of a studied blue water consumption, the blue water footprint in m^3 is multiplied with this characterization factor (Eq. (3)). The following paragraphs summarize the calculation of the characterization factors in Boulay et al. (2018).

First, the difference between freshwater availability and demand (Availability Minus Demand, AMD) is estimated for a certain watershed and month:

$$\mathrm{AMD} = \frac{\mathit{Availability} - \mathit{Human\ Water\ Consumption} - \mathit{Environmental\ Water\ Requirements}}{\mathit{Area}} \left[\frac{m^3}{m^2 month}\right] \tag{1}$$

"Availability – Human Water Consumption" represents the amount of water remaining available after human water consumption has been satisfied in the watershed. It is estimated with the monthly long-term average streamflow at the outflow of the watershed in m^3/month, modeled by the global hydrological model WaterGAP2.2 (Müller Schmied et al., 2014) for approximately 11,000 watersheds worldwide. The Environmental Water Requirements in m^3/month represent the water requirements of the ecosystem, estimated using a simple equation based on the naturally available water in the watershed before human water consumption (Boulay et al., 2018). The characterization factor (CF) of a watershed and month is calculated as:

$$\mathrm{CF} = \frac{AMD_{world\ average}}{AMD} \left[\frac{m^3 world - eq.}{m^3}\right] \tag{2}$$

Where $\mathrm{AMD}_{\mathrm{world\ average}}$ is a water consumption-weighted average of the individual AMDs globally. The weighting uses human water consumption, modeled by WaterGAP2.2 for the year 2010. The CFs are dimensionless but are expressed in m^3 world-eq./m^3. Consequentially, the potential impact of a (blue) water consumption is calculated as:

$$WSF = blue\ water\ footprint\ x\ CF\ \left[m^3 world - eq.\right] \quad (3)$$

where the blue water footprint of a given product is expressed in m^3 and the CF of the respective watershed and month in m^3 world-eq./m^3. The unit illustrates how a blue water consumption of 1 m^3 in the specific watershed and month can be translated into m^3 world-equivalents, indicating the potential impact on other water users compared to the impact of consuming 1 m^3 in a hypothetical global average location. A CF for a certain watershed and month of 10 m^3 world-eq./m^3 indicates that consuming one m^3 water here has the same impact as consuming 10 m^3 of water in the global average location. The CF and the WSF therefore are not to be interpreted absolutely, they can only be interpreted relatively (WSF A is larger/smaller than WSF B). CFs for entire countries are obtained by a water consumption-weighted average of the watershed-level CFs.

The AWARE method assumes that the impact of consuming water in a certain region is inversely proportional to the AMD: Where and when the AMD is lower, the potential to deprive other water users of water is higher. This assumption is essential for the interpretation of the results obtained with AWARE: They aim to provide an estimation of potential impacts of water consumption on both humans and the ecosystem at the same time, which is otherwise difficult to calculate explicitly. Furthermore, Eq. (3) only holds for water consumptions that are small compared to the overall water consumption in a watershed and thus do not significantly change the current water scarcity conditions represented by the AMD. For larger water consumptions, a workaround has been presented with so-called “average” or “non-marginal” AWARE CFs (Boulay et al., 2020). These do not represent a marginal water consumption at the current conditions of the watershed, but the average impact over the entire human water consumption in that watershed and month, leading or at least contributing to the current conditions.

As does the WEFE index, this study concerns the water consumption of entire countries (and their agricultural sectors). Since these water consumptions are non-marginal, i.e., a large part of the entire water consumption in a region, this study employs the non-marginal AWARE country CFs as published by (Boulay et al., 2020) to obtain WSFs. The calculation of the non-marginal CFs is based on the same input data as the marginal CFs but adds a layer of complexity: The equation for the CF (Eq. (2)) is integrated over the Human Water Consumption (HWC) and then divided by it to obtain the average impact per m^3 of HWC:

$$CF_{non-marginal} = \frac{AMD_{world\ average}}{HWC_{total}} \int_0^{HWC_{total}} \frac{1}{AMD} dHWC \quad \left[\frac{m^3 world - eq.}{m^3}\right] \quad (4)$$

Where HWC_{total} is the same value as HWC in Equation (1) (the current human water consumption in the watershed and month) and AMD is a function of HWC. Further detail on the calculation of the non-marginal CFs is provided in the Supplementary Information of Boulay et al. (2020).

This article aims to showcase benefits and tradeoffs of using the AWARE method in the context of WEFE nexus. Therefore, the total water consumption of mediterranean countries is assessed with the AWARE method and later compared to WEFE nexus indicators. Furthermore, a set of important agricultural products and their WSF resulting from irrigation is calculated – first for domestic production, and second, in relation to the impact of imported crops –, to illustrate the importance of virtual water trade in the context of WSF's and the WEFE nexus.

2.2.1. National WSF

To be able to compare the WSF approach to WEFE nexus indices on national level in the Mediterranean, national WSFs are estimated for a set of 18 mediterranean countries, using the blue water consumption data available with AWARE (reference year 2010) (Boulay et al., 2018) and a recently updated version of the method called AWARE2.0 (reference year 2019), **currently in review** (Seitfudem et al., 2024). This informs on the sensitivity of the WSF to varying consumption data sources, be it due to differing years or differences in the underlying model. The water consumption of a country X is multiplied by the respective AWARE non-marginal country CF to obtain the national WSF of X. No AWARE2.0 CFs are used. In addition, the national per capita WSF is provided, calculated with population data from AQUASTAT for the respective year (FAO, 2021).

2.2.2. Footprints of agricultural products

To showcase the importance of virtual water trade in the Mediterranean, the WSFs of eight agricultural products are calculated. To this end, average annual blue water footprints of national crop irrigation in the period 2010–2019 are obtained from (Mialyk et al., 2024) for the selected crops, namely wheat, olives, barley, rice, maize, fodder, cotton, and dates. The WSF is calculated analogous to the WSF of countries. Since Mialyk et al. do not report irrigation water consumption for Malta, it is excluded from the analysis. To determine the amount of the imported crop, data on raw product imports are derived as import quantities in metric tons from the FAOSTAT portal (FAO, 2023). For the imported crops, the WSF of irrigation is calculated and compared to the WSF of the domestically produced crops. More information on the mapping of products and countries between the different datasets is provided in Supplementary Information 2.

2.3. Water footprint assessment

The WFA according to the methodology developed by Hoekstra et al. (2011) quantifies the amount of freshwater used in the production of goods and services. Other than the WSF, it does not assess the sustainability or potential impact of this water use and therefore does not require precalculated CFs for the watersheds and months where water is consumed. The WFA differentiates between three types of water use: green, blue, and grey WFs. The green WF refers to the volume of rainwater consumed, primarily through evapotranspiration, during the production process. The blue WF accounts for the volume of surface and groundwater used and then not returned to the same watershed. The grey WF measures the volume of freshwater required to assimilate pollutants and maintain water quality standards. Together, these categories provide a comprehensive assessment of water use impacts on resources.

For presenting the WFA, we focus on national totals (instead of crop-specific analyses). First, the blue national WF is assessed using the blue water consumption data at national level from the AWARE2.0 method (Seitfudem et al., 2024). This is the same data that was used before in the calculation of the national WSFs.

Second, the blue, green and grey WFs of the national agricultural sectors are analyzed. In alignment with the WSF assessment, the dataset of Mialyk et al. (2024) is used for the blue and green WF, considering all the crops cultivated in each nation. The national blue and green WFs of the individual crops as reported in the dataset are added up to estimate the national blue and green WFs of the entire irrigated agriculture.

For the grey WF, the approach suggested by Mekonnen et al. (2016) was applied using data on agricultural nitrogen load provided by Menegat et al. (2022). This method involves calculating the volume of water required to assimilate the nitrogen loads from agricultural activities, ensuring that water quality standards are met. Specifically, the grey WF calculation considers the nitrogen application rates, crop nitrogen uptake, and the potential leaching and runoff of nitrogen into water bodies.

2.4. Water footprint and WEFE correlation analysis

The WFA results at national level are initially evaluated in terms of economic efficiency, calculating the ratio between the blue WF and the GDP. Then the WF obtained with the two approaches is compared with the WEF Nexus Index, developed by (Simpson et al., 2022) and based on data available as of 2019.

This index was chosen for its comprehensive structure, which aligns with the goals of our study. It incorporates 21 indicators across Water, Energy, and Food dimensions, emphasizing both access and availability. Its granularity enables detailed correlation analysis with water footprints, while its focus on resource interdependencies addresses key challenges in the Mediterranean context. In addition, this index is based on 2019 data, ensuring alignment with the temporal scope of our water footprint and water scarcity footprint assessments. These attributes make it well-suited for evaluating the WEFE Nexus in this study.

The index follows a multi-centric framework, comprising three equal pillars: Water, Energy, and Food. Each pillar includes 'access' and 'availability' sub-pillars of equal weight, selected from 21 relevant indicators.

The correlation analysis between the WEF Index and the WF is here developed considering three levels, i.e. index (level 1), sub-pillar (level 2), and indicators (level 3) (Fig. 2). Both blue National WSF and all the WFA results have been analyzed.

In order to cover the environmental dimension of the WEFE Nexus the WF results are also analyzed in terms of their correlation with the Environmental Performance Index (EPI, Wolf et al., 2022). The EPI provides a data-driven summary of the state of sustainability around the world. It comprises three main objectives: environmental health, which measures the protection of human health from environmental harm; ecosystem vitality, which assesses the protection of ecosystems and sustainable resource management; and climate change, which evaluates a country's efforts to mitigate climate change impacts. Each objective is broken down into various categories and indicators, such as air quality, water resources, biodiversity, and greenhouse gas emissions, providing a detailed assessment of a country's environmental performance.

3. Results

3.1. Water scarcity footprints

The following section presents the WSFs calculated with non-marginal country AWARE CFs.

3.1.1. National water scarcity footprint

The range in national WSFs extends over several orders of magnitude. Egypt exhibits the highest national WSF, whereas it is the lowest for Slovenia, Malta and Croatia (Fig. 3). However, the countries' ranking according to per-capita WSF differs from the ranking by absolute WSF. For example, Greece and Libya exhibit a comparatively high per-capita WSF while the absolute WSF is low. While Egypt has a disproportionally high national WSF, this is not due to disproportionally high per-capita water consumption. Moreover, Egypt's non-marginal AWARE CF is high (28 m^3 world-eq./m^3), followed by Malta (27 m^3 world-eq./m^3) and Libya (24 m^3 world-eq./m^3).

For all countries, the WSFs for 2019 are lower than the WSFs for 2010. Deducing a trend from these values is not straightforward, since the consumption values were created with different versions of the global hydrological model WaterGAP2 (Seitfudem et al., 2024). The results however indicate that the ranking between countries is not very sensitive to the model version or the year examined (rank correlation coefficient equals 0.96).

3.1.2. Water scarcity footprint of main crops in the mediterranean

Of all studied countries, Egypt has the highest water scarcity footprint connected to the target crops, while France, Croatia, Cyprus, Israel,

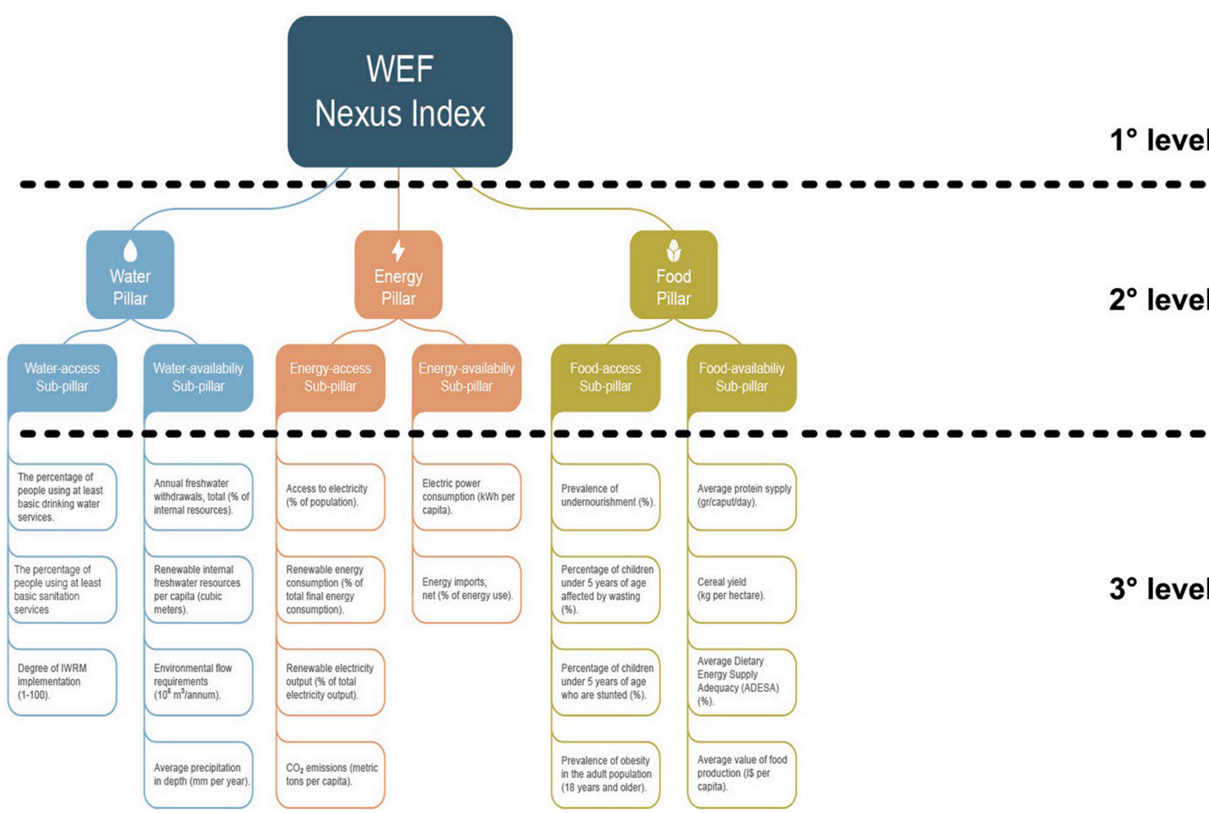

Fig. 2. WEF index structure (adapted from Simpson et al., 2022).

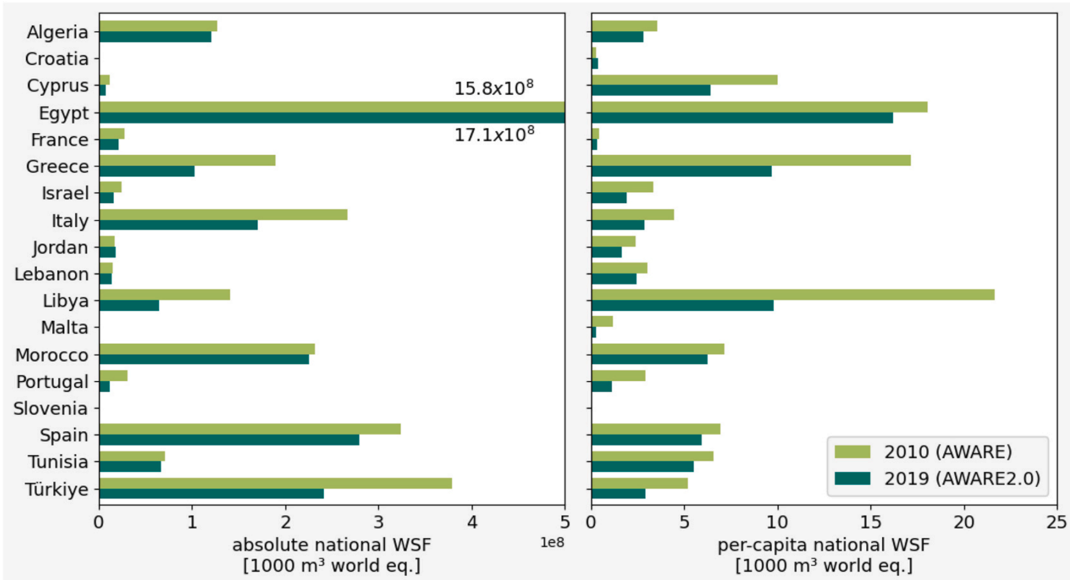

Fig. 3. Left: National WSF, comparing water consumption data of AWARE and AWARE2.0. Right: Per capita national WSF.

Slovenia, Lebanon and Jordan show a comparatively low WSF (Fig. 4). The WSF is a combination of scarcity weighting and volumetric irrigation water consumption. Countries showing a low WSF here seem to only irrigate some of the selected crops. This makes sense since a lower CF indicates higher water availability and thus reduced necessity of crop irrigation. At the same time, some of the crops, such as cotton, are only grown in a subset of the countries. Nevertheless, the ranking of countries is similar if calculating the WSF for all 175 crop types included in Mialyk et al. (2024) (see Supplementary Information 2).

The low domestic water footprint of the selected crops in countries like France, Croatia or Slovenia is accompanied by a much higher water footprint of imports of these crops (Fig. 5). For other countries like Algeria, Cyprus, Egypt, Libya and Morocco, almost all impact linked to the studied crops originates from the domestic production. Figs. 6 and 7 show the two extremes of this analysis: In Algeria, imports of the target crops are responsible for less irrigation water consumption than domestic production, and the CFs of these imports tend to be smaller than the CF of Algeria. The WSF is dominated by domestic production (e.g., Algeria), but this does not mean that there is no import. It rather shows that the water scarcity impact of the crop import is small compared to the domestic impact (see Fig. 6).

France shows the opposite situation with high CFs linked to a high irrigation blue WF of the imports. With Algeria's CF ranked 21st among 209 countries, most of the exporting countries have a lower CF. Furthermore, the target crops' irrigation blue WF is 154 times as large for the domestic production as for the imports. However with France's CF ranked 148th among 209 countries, many of the exporting countries have a higher CF. Furthermore, the target crops' irrigation blue WF is 97% smaller for the domestic production than for the imports.

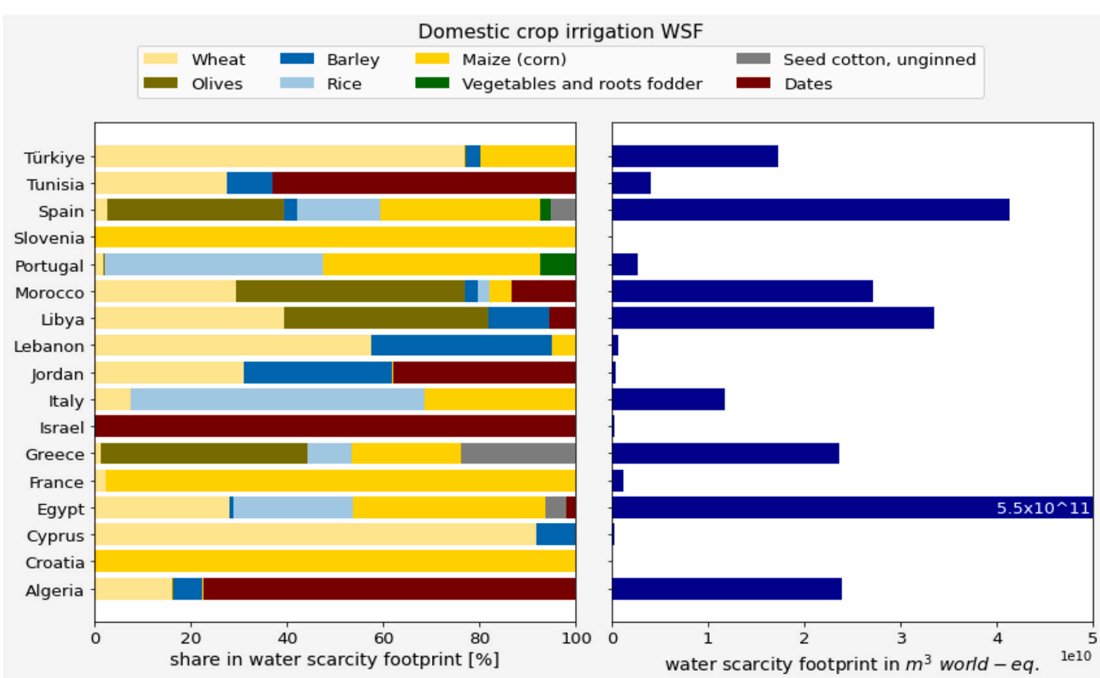

Fig. 4. Left: Share in water scarcity footprint per crop in 17 countries. Right: AWARE water scarcity footprint (m^3 world-eq.) of the irrigation.

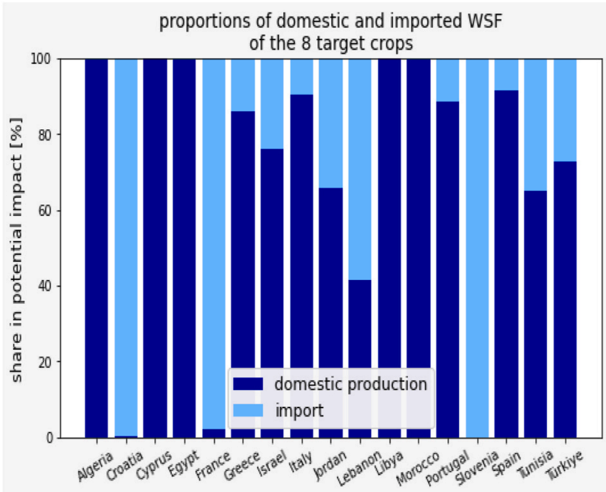

Fig. 5. Share of domestic production and import in the total water scarcity footprint of the target crops, using non-marginal CFs.

3.2. Water footprint assessment

The Blue National WF obtained with the WFA approach provides a general assessment of the consumptive water demand in the Mediterranean regardless of local water scarcity conditions. In general, the results are in line with those already shown in Fig. 3 (i.e. Blue National WSF) but the information on the real volumes consumed in each country provide other interesting insight on the mediterranean situation (Fig. 8). Egypt, Spain, Turkey, Morocco, and Italy appear to be the most water-demanding nations in absolute terms, while Egypt, Greece, Spain, Libya, and Morocco are the most demanding on a per capita basis. The absolute national WF ranking well reflects the WSF apart from the relative position of countries such as France and Greece. On the contrary the per capita consumption shows a different classification of countries with Spain moving to the top three nations in term of consumption per capita or Cyprus that instead shows a lower position.

The WFA of the agricultural sector (Fig. 9) exhibits significant heterogeneity across the analyzed Mediterranean countries. Green WFs generally constitute the largest component for most nations, ranging from approximately 40-50 m3/t in Egypt to exceeding 2000 m3/t in Croatia and Greece. Blue WFs demonstrate considerable variability, with some countries such as Jordan and Egypt displaying elevated values surpassing 1000 m3/t, while others like France and Spain exhibit significantly lower values below 100 m3/t. Grey WFs typically represent the smallest component, yet still manifest notable inter-country disparities, ranging from negligible quantities in some nations to over 60 m3/t in Croatia. It is noteworthy to remind that the presented Grey WF does not account for the industrial section and is seldomly based on the nitrogen leaching dilution requirement.

Significant inter-country variations are also observed in total WFs and the relative proportions of green, blue, and grey components. For instance, Portugal presents a relatively balanced distribution across the three footprint types, whereas Egypt's footprint is predominantly characterized by blue water consumption.

3.3. Water footprint and WEFE correlation analysis

3.3.1. Economy efficiency of water

The Economic Efficiency of Water use is high (i.e. low values of the indicator) in the case of Malta, Slovenia and Israel (Fig. 10), with problems of efficiency of water use in southern Mediterranean countries. The high values for the southern Mediterranean countries indicate that there are issues regarding the efficiency of water use.

3.3.2. Water footprint and water scarcity footprint at first level

Looking at Fig. 11, the WSF displayed a high negative correlation with both WEF index average (−0.45 for AWARE and −0.41 for AWARE20) and the Water index (−0.45 in both cases). As for the WFA derived results, the Green WF demonstrates a moderate positive correlation with the WEF index average (0.40*) and moderate positive correlations with the Water Index (0.44*). Grey WF exhibits strong positive correlations with the WEF index average (0.82*), GDP per capita (0.68*), EPI index (0.70*), Water Index (0.87*), and Food Index (0.73*). Blue WF is strongly negatively correlated with the WEF index average (−0.72*) and moderately negatively correlated with GDP per capita (−0.40*), EPI index (−0.45*), Water Index (−0.61*), and Food Index (−0.58*). In general, the WFA components displayed higher levels of correlations with the several components and indicators of the nexus than the WSF components.

3.3.3. Water footprint and water scarcity footprint at second level

In Fig. 12, the National Blue WF AWARE exhibits negative correlations with water availability (−0.22), water access (−0.21), and food access (−0.20), while showing a moderate positive correlation with food availability (0.33). National Blue WF AWARE20 shows similar patterns with negative correlations to water availability (−0.25), water access

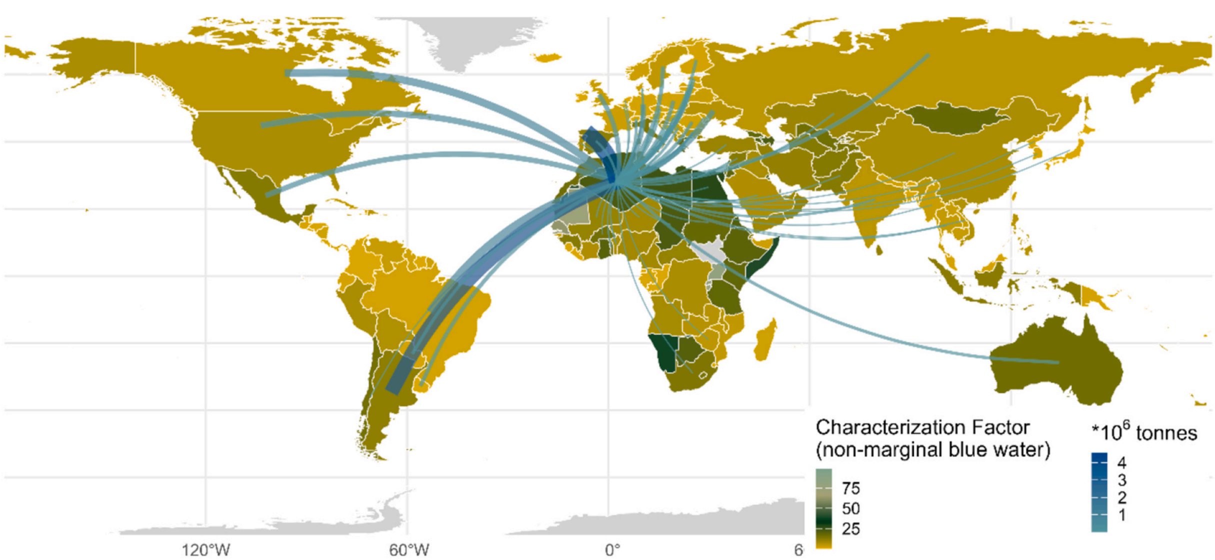

Fig. 6. Blue water linked to Algeria's import of the target crops.

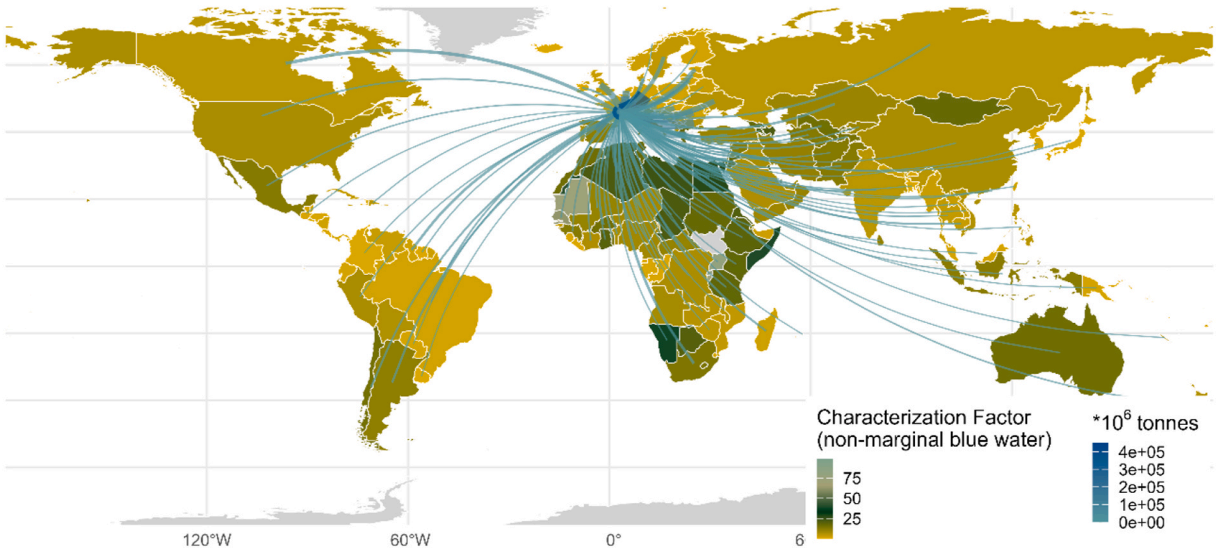

Fig. 7. Blue water linked to France's import of the target crops.

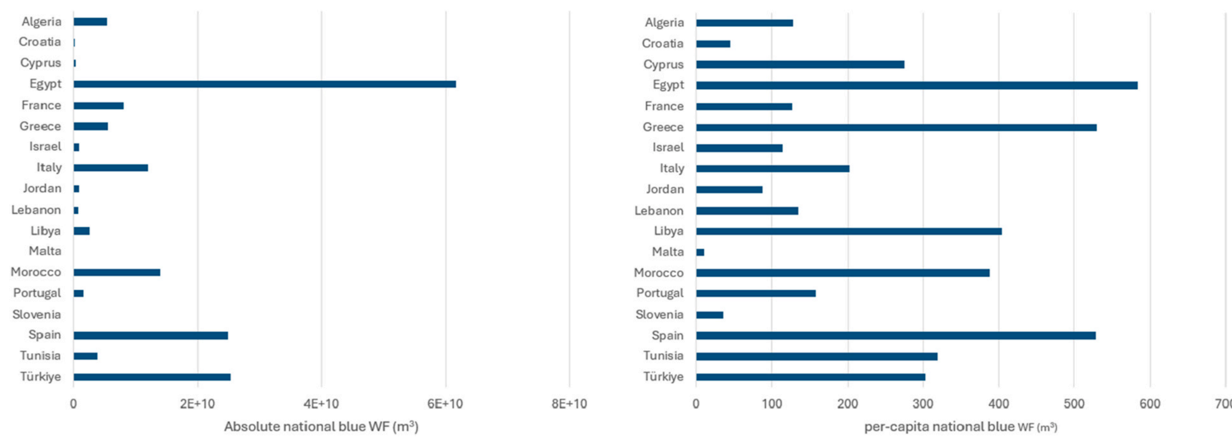

Fig. 8. Left: National blue WF, Right: Per capita national blue WF.

(−0.25), and food access (−0.27), and a weak positive correlation with food availability (0.22).WSF AWARE20 shows a significant negative correlation with water availability (−0.50*) and moderate negative correlations with food availability (−0.41) and food access (−0.16). WSF AWARE exhibits strong negative correlations with water availability (−0.58*) and food availability (−0.41), along with moderate negative correlations with food access (−0.15) and energy access (−0.32). Green WF demonstrates a moderate positive correlation with water availability (0.42*), water access (0.39*), food availability (0.45*), and energy access (0.33*). Grey WF shows strong positive correlations with water availability (0.82*), water access (0.67*), food availability (0.75*), and food access (0.60*), along with moderate positive correlations with energy access (0.61*). Blue WF exhibits strong negative correlations with water availability (−0.72*), food availability (−0.56*), and energy access (−0.59*), along with moderate negative correlations with water access (−0.24*), food access (−0.49*), and energy availability (−0.24*). The results underscored that Blue WF is generally negatively correlated with water and food access and availability, while Green and Grey WF show positive correlations with these indicators, highlighting their importance in enhancing resource availability and access.

3.3.4. Water footprint and water scarcity footprint at third level

In Fig. 13, the WSF AWARE and AWARE2.0 show a significant negative correlation with precipitation (−0.47* and −0.5*, respectively). Green WF demonstrates positive correlations with several indicators, including IWRM implementation (0.51*), freshwater resources (0.48*), renewable energy consumption (0.52*), and negative correlative with stunting of children (−0.64*), but a negative correlation with renewable electricity (−0.49*). Grey WF shows strong positive correlations with basic drinking water (0.62*), IWRM implementation (0.58*), renewable energy consumption (0.57*), electricity access (0.5*), and protein supply (0.56*). However, it also has significant negative correlations with freshwater withdrawals (−0.50*), undernourishment (−0.55*), and wasting (−0.67*). Blue WF exhibits negative correlations with several indicators, including freshwater resources (−0.46*), environmental flow (−0.71*), and renewable energy consumption (−0.51*), but positive correlations with obesity (0.41*), undernourishment (0.4*), and wasting of children under 5 (−0.55*). The third level of analysis confirms that the food sector indicators have the highest correlation values. Notably, Green and Grey WF show strong positive correlations with multiple sustainability indicators, while Blue WF is negatively correlated with key indicators.

4. Discussion

The application of the two main existing methodological perspectives on the water footprint (i.e., WFA and LCA-WF) for the Mediterranean and its comparison with the multiple WEFE dimensions (here represented by the WEF index and the EPI) shows the complementarities

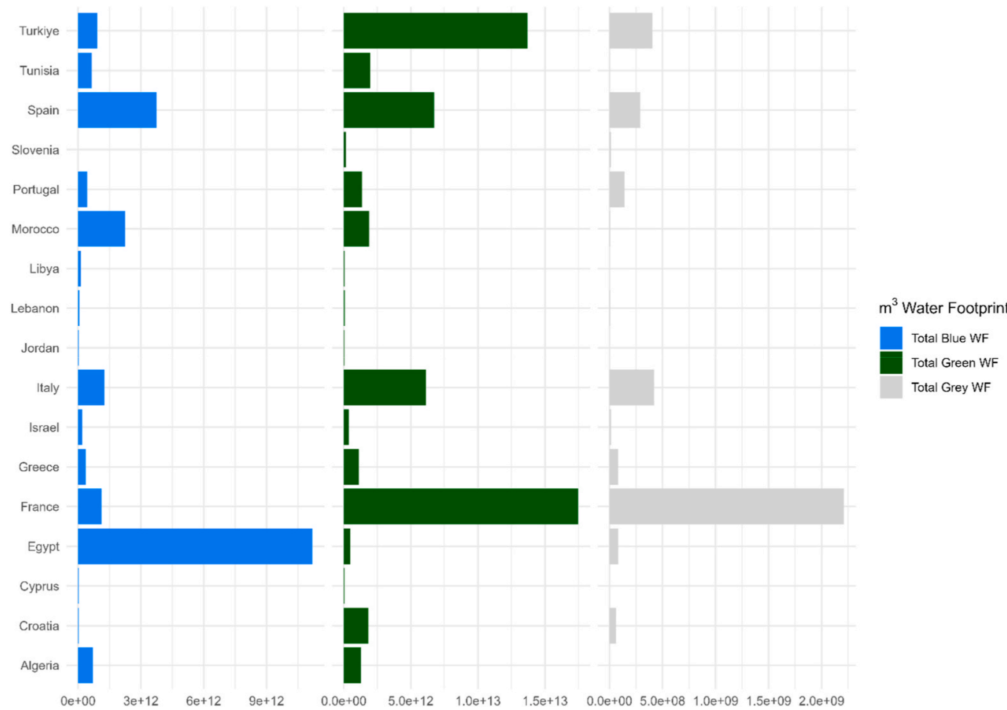

Fig. 9. Agricultural Blue, Green and Grey WF presented for the mediterranean countries studied.

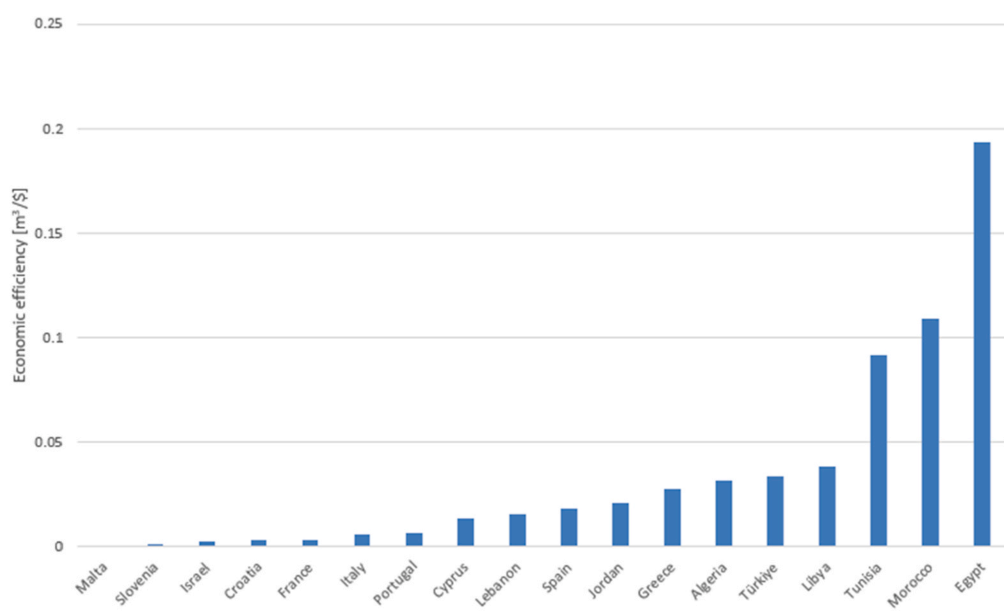

Fig. 10. Economic efficiency of water use.

of the two concepts. On one hand, WF and WSF highlight the international dimension of the WEFE Nexus revealing environmental impacts that transcend national borders. On the other hand, the WEFE Nexus concept offers valuable insight into water related topics not covered by the water footprint.

The discussion therefore explores the WF and WSF of the Mediterranean region (section 4.1) and highlights their correlation with the other Nexus dimension (section 4.2). How the uptake of the WF concept in policy could support the shifting towards a more nexus-based approach is then discussed (section 4.3) highlighting the existing limitations in WFs evaluations (section 4.4).

4.1. Assessment of water footprints

The WF and WSF results show considerable disparities in terms of water availability and consumption among mediterranean countries, in line with the existing literature (UNEP/MAP and Plan Bleu, 2020). Egypt exhibits the highest WF and WSF on a national level and for the studied crops indicates its severe water stress and heavy irrigation dependence. In contrast, countries such as Croatia, Cyprus, Israel, Slovenia, Lebanon, and Jordan demonstrate comparatively low WF and WSF's, reflecting better water availability or lower irrigation requirements. It is important to underline how the WSF highlights the different effects water consumption can have in different water scarcity contexts. The same volumetric WF can assume considerably different meaning in relation to the

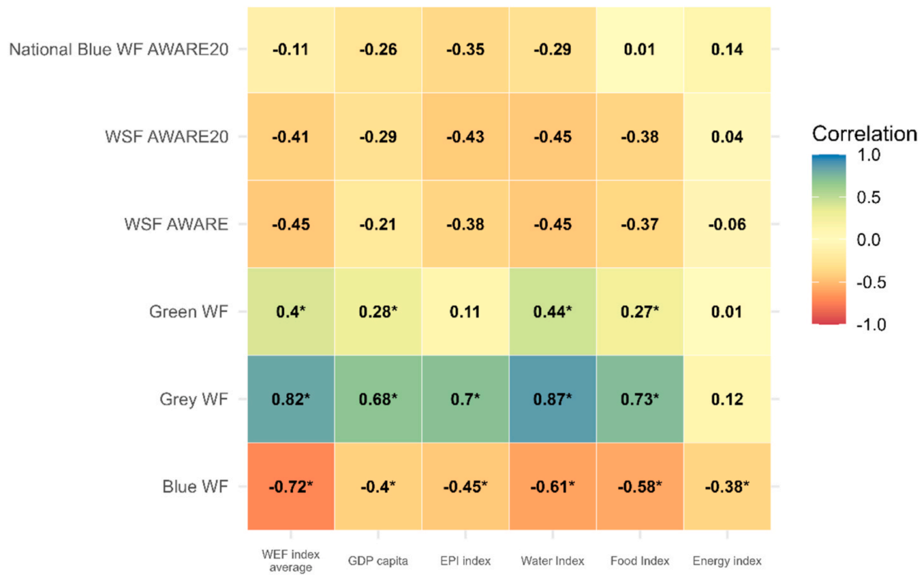

Fig. 11. Correlation matrix (Spearman's rank 95% confidence- level I).

Fig. 12. Correlation matrix (Spearman's rank 95% confidence- level II).

local water availability. For example, when comparing the Blue National WF of Greece and France, France exhibits a higher WF in absolute terms. However, when considering the WSF, the rankings are reversed, indicating that water consumption in Greece is less sustainable due to the local water scarcity issues.

The disparity between total and per capita WSF and the influence of high AWARE CFs underline the need for targeted water management policies. As an example, the focus for Egypt should not only be on reducing total water consumption but also on improving water use efficiency and reducing the impact of water consumption on scarce resources. This could involve adopting technologies and practices that enhance water conservation and promote sustainable water use across different sectors.

Moreover, the present study uncovers a dichotomy in domestic versus imported water footprints for certain crops: While countries like France and Croatia show low domestic WSFs, they exhibit high water footprints for imports, indicating a reliance on external regions with potentially higher water stress. Conversely, countries such as Algeria, Cyprus, Egypt, Libya, and Morocco show that almost all water scarcity impacts stem from domestic production, underscoring the pressure on local water resources. This highlights the need for sustainable irrigation practices, diversification towards less water-intensive crops, and international cooperation to manage global water resources effectively. Governments should implement policies promoting efficient water use in agriculture and support sustainable practices in regions from which they import crops, thereby working towards a balanced and sustainable global agricultural water scarcity footprint. While the WF approaches emphasize the importance of international supply chains and product origins, the WEFE Nexus is often limited to a national perspective. As also shown by D'Odorico et al. (2018) the expanding influence of globalization in the food system complicates the connections between water, food, and energy by separating consumers from production,

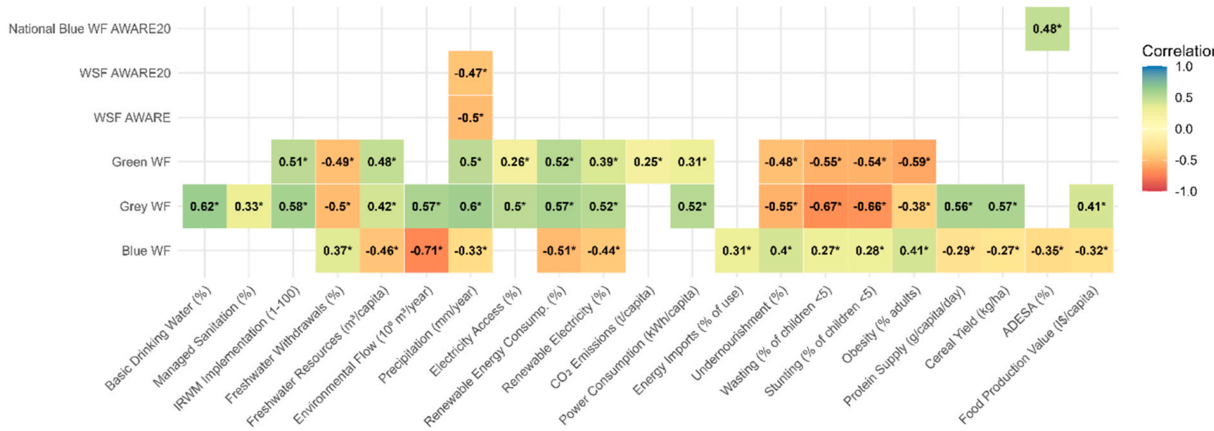

Fig. 13. Correlation Matrix (Spearman's Rank 95% Confidence- Level III). Only significant correlations were shown here for the sake of clarity.

relocating land and water use across borders, and masking the environmental effects of consumption. By learning from the WF approaches, the WEFE Nexus approach could be extended to include international dependencies in the water, food and energy sectors.

4.2. Correlation between WF and nexus related indicators

The results reveal that water scarcity footprint (WSF) can be significantly linked to multiple WEFE Nexus dimensions. This has been demonstrated by the negative correlation between WSF and WEF Nexus Index. A high WSF indicates significant stress on water resources, and therefore a need for sound water management practices. The stress on water resources leads to a reduced WEFE index, as water scarcity disrupts the balance and interdependencies among water, energy, food production, and ecosystem health. In scenarios where the water scarcity footprint is elevated, it becomes challenging to maintain sustainable agricultural practices, energy production, and ecosystem services, leading to a decline in the WEFE index. Thus, a high WSF not only highlights issues regarding water use but can point to broader systemic challenges, necessitating integrated and sustainable management approaches to enhance resilience and overall resource efficiency.

The WSF, based on the LCA framework, not only quantifies the impact of blue water use in relation to local water scarcity, it also points towards other systemic issues, such as energy intensity of the water use. In water-scarce regions, more energy is required to satisfy water requirements, such as by pumping water over large distances or by desalination. While this is an implicit message in WSFs, the broader LCA framework addresses impacts of energy use more explicitly, albeit not attributing an intrinsic burden to energy use. For example, fossil energy use is accounted for in the LCA impact category of mineral resource depletion (Bulle et al., 2019).

The results indicate that a comparatively high value of the green WF, which refers to the volume of rainwater consumed during crop production, can be an indicator of sustainable water use. It signifies that a country relies more on naturally available water than on surface or groundwater extractions, requiring less artificial irrigation and minimizing stress on surface and groundwater resources. This reliance on rain-fed agriculture lessens environmental impact by preserving aquatic ecosystems and reducing energy consumption associated with water extraction and irrigation systems. Consequently, countries with a high green water footprint can maintain agricultural productivity while promoting environmental sustainability. The positive correlation of the food and water sub-pillars with the green WF seems to corroborate this finding. However, green water use should be interpreted as use of a limited resource (Hoekstra and Mekonnen, 2012b) and be properly managed within its sustainable limits (Wang-Erlandsson et al., 2022).

The grey agricultural WF is significantly associated with the WEF Nexus Index (correlation coefficient 0.73), suggesting that regions with higher water availability and better access tend to experience more water pollution. This correlation is likely due to increased agricultural activity in these regions, leading to greater wastewater generation and pollutant runoff. The increased intensity of agricultural activities in water-abundant areas lead to greater fertilizer and pesticide application. These inputs contribute significantly to the nitrogen load, which drives the grey WF calculation. Consequently, managing grey WF is crucial in such areas to balance the benefits of abundant water resources with the need to control pollution and maintain water quality. Water quality receives less attention and detail within the WF concept and associated databases compared to water quantity. This is largely due to the complexity of water pollution, which involves a wide range of pollutants, their various uses, and behaviors. Incorporating water quality aspects into water footprint assessments is a challenging endeavor. However, it is worth noting that water quality issues are a growing concern globally, alongside water quantity, posing risks to both the environment and human health (Schwarzenbach et al., 2010; Lin et al., 2022; Macias et al., 2022; Rhouma et al., 2024). In the LCA framework, there are indicators for potential impacts of water pollution, such as for eutrophication or acidification. The potential added value of these indicators to the WEFE Nexus approach could be studied in a follow-up work.

The blue agricultural WF shows a negative correlation with the WEF Nexus Index, as well as with individual indexes of water, energy, and food. This indicates that regions with higher blue WF tend to have lower scores in these indexes, reflecting unsustainable water usage that strains water resources, energy production, and food systems. The blue WF is also negatively correlated with the EPI, highlighting the broader environmental impacts of over-reliance on blue water sources. Excessive consumption of blue water leads to the depletion of vital water bodies, increased energy demands for water extraction and irrigation, and reduced agricultural sustainability, collectively undermining environmental health and resource efficiency. Therefore, reducing the blue WF is essential for improving the WEF Nexus Index and overall environmental performance.

4.3. Policy and water footprints

The water footprint assessment serves as a valuable tool for governments to comprehend how diverse production processes contribute to the overall water footprint within different river basins across the nation. In addition, it aids in identifying the final products associated with water consumption and pollution within these basins (Garrido et al., 2010; Chapagain and Tickner, 2012; Swain and Tripathy, 2024).

In the direction of assuming a more integrated perspective in water management, Spain has taken a pioneering step by incorporating water footprint assessments into policy-making processes, making it a fundamental component in the development of river basin plans (Garrido et al., 2010).

A critical concern, particularly in water-scarce basins, revolves around the judicious allocation and utilization of water resources (Sanchis-Ibor et al., 2022). This entails safeguarding minimum environmental water requirements and quality standards while maximizing the societal benefits derived from water consumption. Often, certain contributors to the overall water footprint within a basin prove to be less efficient. This inefficiency becomes apparent, for instance, when scarce water resources are needlessly polluted or utilized for the production of low-value, water-intensive export goods. In such scenarios, the utility derived from water usage is minimal, while the associated environmental and societal costs are substantial.

Shifting the focus from the water footprint within a country or river basin to that of the consumers residing in these areas unveils the interconnectedness between consumption patterns and water depletion and pollution issues elsewhere (Zucchinelli et al., 2021). Pointing out the global dimension of water management (Hoekstra and Chapagain, 2011), WFs can foster a more integrated, nexus-based approach, where water, energy, and food systems are managed holistically, considering their multiscale interdependencies to optimize resource use, enhance sustainability, and reduce environmental impacts globally. Indeed, by tracing the hidden water usage embedded in imported products, governments are confronted with the challenge of ensuring the sustainability of imported commodities from a water resources perspective. This necessitates the development of mechanisms to guarantee that imported goods align with sustainable water management principles.

Virtual water trade allows water-scarce regions to import water-intensive products instead of producing them domestically, thereby reducing their actual water consumption. There are two compelling reasons why understanding the water footprint of traded commodities is garnering increasing attention. Firstly, water-scarce nations are compelled to reassess the relationship between trade and domestic water scarcity. Notably, countries facing water scarcity can alleviate domestic pressures by externalizing their water footprint through increased reliance on virtual water imports. Secondly, consumers are displaying a growing interest in sustainable products, prompting inquiries into the origins, production methods, and sustainability of water footprints associated with various production stages.

Sustainability, in this context, entails meeting environmental flow requirements and adhering to ambient water quality standards within the catchments where production occurs. It also necessitates the prevention of social conflicts over water and the avoidance of unnecessary waste or pollution of water resources. This dual emphasis on environmental integrity and social harmony underscores the importance of ensuring that water footprints throughout the production chain are ecologically sound and socially responsible.

4.4. Limits of this study

Water scarcity impact indicators such as AWARE are subject to substantial uncertainty. The uncertainty results from the input data (that is, roughly said, the outputs of two global hydrological models) and the assumptions and simplifications made in the calculation process of AWARE (Boulay et al., 2021). As an example, while estimating the potential to deprive other users with the consumption of a m^3 of water in a certain region, AWARE does not explicitly consider how many potential other users are in this region or how vulnerable they are to changes in water availability (Boulay et al., 2018). These aspects are however covered in the WEFE indicator, which is why this study aims to integrate both approaches. Furthermore, AWARE studies should, wherever possible, be conducted on watershed resolution. The use of nationally aggregated CFs in this study hides that water scarcity issues are not contained by political borders and the water consumption in one country could affect another country. Moreover, the national water consumption data representing the blue water footprint in this study is only approximate and would not allow a more detailed study. This is due to the origin of the data: It was simulated in the global hydrological model on a comparatively coarse grid of $0.5^\circ \times 0.5^\circ$ and then reaggregated into country values.

A further limitation of the WSFs in this study concerns the crop water footprints. Since the national CFs were aggregated from watershed values using the spatiotemporal pattern of total (domestic, industrial, manufacturing, energy, irrigation) water consumption, they might misrepresent the spatiotemporal water consumption patterns of individual crops and thus their potential impacts. A second source of uncertainty of the crop WSFs is the irrigation water consumption data. Irrigation water consumption data is difficult to generate since it is not directly measured. Therefore, it relies on assumptions of crop models and national estimations, as in the case of the data used from (Mialyk et al., 2024). However, the authors assume that the overall WSF data quality is sufficient for the purpose of comparing correlations between different indicators as done in this study. When comparing the import and domestic production WSF of the target crops, it was assumed that the exporting country produced these crops. However, this does not need to be true for the entirety of the export. Therefore, the affected assessment can only be an estimation.

There remains a policy-related limitation of the use of AWARE to compare countries. Countries “are where they are” and a large part of their water availability and thus AWARE CF is determined by local climate. This means that naturally there will be some countries with higher WSFs, and this is not necessarily “bad”, as long as it is handled responsibly.

There are limits to the volumetric WF concept as well. Due to data availability, national water footprint accounting often does not address all types of water use. One example is the evaporation of water from hydropower reservoirs, which this study does not account for as well. According to Vanham (2016), water footprint accounting could be extended to the water use of aquaculture, wild foods, hydropower, biomass for energy and other sectors. Furthermore, the concept of the grey water footprint has been criticized for being simplistic compared to the actual mechanisms of water pollution and not suitable for some pollutants (Ridoutt and Pfister, 2013). Similarly, green water footprints are difficult to measure directly and instead require modeling or assumptions about evapotranspiration from plants and soil (Quinteiro et al., 2015).

Moreover, the concepts of "water scarcity footprint" and "water footprint" as employed in this paper do not distinguish between the two types of blue water: surface water and groundwater. This distinction is crucial because groundwater, unlike surface water, requires significant energy for extraction, pumping, and distribution. Surface water, found in rivers, lakes, and reservoirs, is generally more accessible and requires less energy to manage compared to groundwater. Understanding this difference is essential for a comprehensive assessment of water use and its environmental impact. By acknowledging the energy demands associated with groundwater, we can better evaluate the full environmental footprint of water consumption and implement more effective water management practices.

To gain more insight into the national WF, some of its components could be split up by attributing them to either food security, water security or energy security. In the context of food security, this could involve, for example, separating cooking or dishwashing from the municipal water use. Similarly, the component of tree biomass used for energy could be separated, specifically focusing on how that energy contributes to food security. However, it is evident that implementing this approach would necessitate a considerable amount of data, which is often not readily available in practice.

While the input data quality of this study is limited, it is suitable for the scope of this study: Showcasing potential benefits of considering WF and WSF in the WEFE nexus framework. For a more in-depth analysis of virtual water trade and water scarcity in the Mediterranean, additional data could be used, such as from AQUASTAT or national water statistics. Further studies could also benefit from comparing different methods for the WSF in addition to AWARE, e.g., the Water Stress Index (Pfister and Bayer, 2014).

In section 3.3, the similarity between WEFE nexus indices and the WF/WSF results was only assessed with the correlation coefficient. However, the correlation coefficient assumes linear relationships between assessed variables. It is possible that non-linear relationships exist between the WEFE nexus indicators and the WSF which were not discovered in this analysis. In future studies, based on detailed local assessments of WF and WSF, additional metrics could be used to establish similarities and differences with the WEFE nexus indices and potentially explore seasonal dynamics.

Additionally, the study primarily focuses on the water and agricultural dimensions of the Nexus, with less emphasis on energy and ecosystem components or feedback loops within the system. To address these gaps, future research should utilize higher-resolution datasets, explore disaggregated surface and groundwater impacts, and incorporate broader Nexus components such as energy footprints and ecosystem impacts. Moreover, expanding the analysis to include virtual water trade sustainability and applying the WF-WEFE Nexus framework in real-world case studies with stakeholder input can strengthen its relevance and applicability for global and regional policy formulation.

5. Conclusion

This study highlights the critical importance of integrating the existing WF approaches (i.e. WFA and WSF) with the WEFE Nexus to advance water resource management strategies.

By analyzing both volumetric and scarcity-weighted water consumption across Mediterranean countries, the research uncovers key disparities in water use, emphasizing the contextual relevance of local water availability and scarcity.

The findings reveal significant disparities in WSFs among Mediterranean countries, highlighting the varying impacts of water consumption based on local water availability. Countries such as Egypt, with the highest WSF, face acute water stress due to heavy reliance on irrigation and limited water availability. Conversely, nations like France and Croatia demonstrate lower domestic WSFs but significant dependencies on imported water-intensive crops, often originating from water-scarce regions. These insights underscore the interconnectedness of local and global water systems, emphasizing the need for sustainable practices in both domestic water use and virtual water trade.

The strong correlations identified between WF and WEFE indicators highlight how these metrics can serve as critical tools for understanding and managing interdependencies between water, energy, food, and ecosystems. By linking WSF with WEF Nexus indicators, policymakers can assess how water use affects food production, energy demands, and ecosystem health, enabling more integrated and informed decision-making.

Moreover, the analysis of virtual water trade underscores the interconnectedness between domestic consumption and global water resources. Countries with low domestic WSF but high imported WF, like France and Croatia, must ensure the sustainability of their imported goods. This calls for international cooperation and the promotion of sustainable practices in regions from which they import crops.

In conclusion, integrating the WF concept with the WEFE Nexus is essential for developing effective strategies for sustainable water use, particularly in regions like the Mediterranean. By leveraging detailed assessments and understanding water scarcity characterization factors, targeted interventions can be prioritized to promote sustainable water use practices and enhance overall resource efficiency.

Based on these findings, several policy recommendations are proposed. First, Water Footprint metrics should be integrated into national policies by incorporating them into river basin management plans, as seen in Spain's water footprint strategy, and mandating periodic WF assessments for water-intensive sectors. Second, regulating virtual water trade for sustainability is crucial. This can involve developing certification systems for water sustainability in international trade and embedding these into trade agreements with exporting countries. Third, strengthening regional cooperation on WEFE Nexus policies is recommended, such as establishing a Mediterranean WEFE Task Force to facilitate data sharing, joint policy development, and the implementation of Nexus-based solutions. Lastly, green and grey water management should be incorporated into policies by introducing incentives for rainfed agriculture and enforcing stricter regulations on agricultural nitrogen runoff through penalties and remediation programs.

CRediT authorship contribution statement

Ali Rhouma: Writing – original draft, Methodology, Conceptualization. **Georg Seitfudem:** Writing – review & editing, Data curation. **Jerome El Jeitany:** Writing – review & editing, Data curation. **Tommaso Pacetti:** Writing – review & editing, Methodology. **Floor Brouwer:** Writing – review & editing. **José M. Gil:** Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.indic.2025.100640.

Data availability

Data will be made available on request.

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