



Crafting a water footprint database of foods in Spain to drive sustainable consumption

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ABSTRACT

Food, a cornerstone of human existence, plays a central role in health, social progress and cultural identity. Despite its vital role, the production and consumption of food has a significant environmental footprint, requiring metrics such as water footprints for sustainable practices. The water footprint of a food product is the amount of water that is consumed and polluted in all of the processing stages. This paper introduces the first comprehensive database of water footprints for 158 food commodities commonly consumed in Spain. Developed using a standardized methodology, the database integrates up-to-date production and trade data (2022) with water footprint data from the global assessment by Mekonnen and Hoekstra (2010, 2011), brought to the same reference year using the fast-track method. It represents a novel approach in that it covers a wide range of food categories, specific food types and varieties, while also taking into account local agricultural practices, and climatic and geographical factors, providing a highly detailed analysis of both the imported and exported water footprints associated with each. By facilitating the evaluation of the influence of dietary modifications on global water scarcity, this database provides a foundation for the formulation of evidence-based policies aimed at fostering sustainable food systems.

1. Introduction and literature review

Food is a fundamental component of human health, societal development and cultural heritage, serving as a linchpin of the global economy. However, the production and consumption of food exert substantial environmental pressures, contributing significantly to climate change, water scarcity, deforestation, land use, and biodiversity loss (Poore and Nemecek, 2018; Springmann et al., 2018; Gibin et al., 2022). These impacts underscore the necessity for effective metrics and robust data to comprehend and mitigate the environmental footprint of global food production (Halpern et al., 2022).

A pivotal metric for assessing the environmental impact of food is the water footprint (WF) (Mekonnen and Gerbens-Leenes, 2020). It provides a comprehensive understanding of water resource utilization and its associated environmental implications (Ingrao et al., 2023). The WF is categorized into three primary components. The green WF is the volume of rainwater stored in the soil that is used by plants through evapotranspiration. The blue WF quantifies freshwater extracted from surface and groundwater sources, including water evaporated, incorporated into products, or transferred to other water bodies. The grey WF assesses

the volume of freshwater required to dilute pollutants generated during the production to meet water quality standards (WFN, 2020). By facilitating comparisons of the environmental performance of diverse food commodities and dietary patterns, the WF informs evidence-based policies and strategies to advance sustainable food systems (Vanham and Leip, 2020).

Research on the WF of the food sector has shown that the production of animal-based foods requires significantly more water than plant-based alternatives. Pioneering work by Mekonnen and Hoekstra (2010, 2011) quantified water uses in crop and livestock production, highlighting the environmental impact of meat consumption. Subsequent work by Poore and Nemecek (2018) reinforced these findings, demonstrating the potential for plant-based diets to reduce water consumption. FAO has been instrumental in promoting the WF concept globally, refining methodologies and integrating this approach into broader environmental assessments (Hoekstra et al., 2011). Recent research, such as Mialyk et al. (2024), have further deepened our knowledge by revealing significant variations in water use across 175 crops over a three-decade period. This underscored the necessity for bespoke water management strategies tailored to the specific needs of

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each crop and to accommodate changing environmental conditions. Moreover, [Pettersson et al. \(2021\)](#) developed a comprehensive dataset detailing the carbon footprint and WFs of various food commodities. This resource supported the development of sustainable food systems by providing detailed information on the environmental impacts of food from production to consumption.

Despite the significance of the WF, data availability and quality vary significantly among different foods and regions. For instance, [Harris et al. \(2020\)](#) assessed the WFs of various global dietary patterns by consolidating data from multiple life cycle assessments. The study found that European and Oceanian diets have the highest WFs, while Asian diets have the highest blue WFs. Healthy diets, as recommended by national guidelines have lower green WFs compared to average diets, but there is no difference in blue WFs. Therefore, assessing WFs at the country level is critical to enabling tailored water management strategies, addressing localized water scarcity issues, supporting sustainable development and informing decision-making.

Spain faces a critical challenge of water scarcity, exacerbated by the intensive demands of its agricultural sector ([Cazcarro et al., 2015](#)). With a climate ranging from Mediterranean to semi-arid, water availability varies widely across the country. Regions heavily dependent on agriculture, such as Andalusia and Murcia, face acute water stress. Water-intensive crops, such as almonds, rice and olive oil, further stress these arid ecosystems. Over-exploitation of water has led to serious environmental consequences, including the depletion of aquifers and the degradation of wetlands, as exemplified by the shrinking Doñana National Park ([De Stefano and Llamas, 2013](#)).

In order to address the critical issue of water scarcity in Spain, it is essential to gain a comprehensive understanding of the volume of water consumed in the food sector. Despite the existence of global studies on calculating the WFs of food products, a detailed and specific database for the foods consumed in Spain, which accounts for local climatic and geographic factors, delves into specific varieties within food categories such as cuts of meat or types of cheese, and considers the volumes of imports and exports, does not currently exist. This is important because many of the products consumed in Spain are imported from other countries, each of which has a different WF influenced by its origin and local agricultural practices. This approach enables the evaluation of the WF of production in other countries, providing a more comprehensive perspective on the sustainability of Spain's food trade. Furthermore, by adjusting transport distances and routes to Spain, the database allows for a more accurate calculation of the WF associated with food transport, helping to better understand how imports of certain products may have higher water costs due to their distance from the place of production.

Thus, the objective of this paper is to create a standardized WF database for food commodities consumed in Spain, taking into account imports and exports, and considering a wide range of product types and variations – such as different cuts, grades or processing levels. By applying a consistent methodology and following the guidelines of the international Water Footprint Network, the database ensures comparability and reliability, serving as the foundation for a national water use data network within the food sector, thereby improving water planning and management at the national level in Spain. It also provides a local model that could be extended to global initiatives, promoting the exchange of best practices and water management strategies between countries.

Building upon prior research examining food consumption patterns in Spain and their associated environmental footprints ([Blas, 2019](#); [Blas et al., 2018, 2019](#); [Camporesi and Bordon, 2025](#); [Cazcarro et al., 2012, 2014](#); [García-Herrero et al., 2023](#); [Garrido et al., 2010](#); [González-Martínez et al., 2024](#); [López et al., 2022](#); [Salmoral et al., 2011](#); [Vanham et al., 2013, 2016, 2021](#)), this updated database introduces greater product differentiation, and provides insights into regional and product-specific production practices, particularly through more precise data on imports and their associated environmental costs. The availability of such data empowers consumers to choose products with lower WFs,

thereby promoting more sustainable consumption practices. Ultimately, this resource will support Spain's commitment to reducing the environmental impact of food production and consumption while advancing Sustainable Development Goals.

2. Materials and methods

2.1. Step 1. Database composition and food classification

A food database was created using data on food consumption by residents in Spain for the year 2023 ([Ministry of Agriculture, 2023a](#)). The database comprises a complete inventory of 158 products. Each food item was categorized by food group and food typology, and all details were recorded in an Excel spreadsheet (see **Supplementary dataset**).

2.1.1. Group categories

The group classification includes broad categories of food products that may be of particular interest to different stakeholders ([Pettersson et al., 2021](#)). The database contains four main groups: 1) agricultural processed, mainly plant-based, industrially processed foods 2) animal husbandry, products of terrestrial animal origin 3) crops, fresh or minimally processed plant products 4) fishing, products derived from both fresh and salt water.

2.1.2. Food typology

Typology represents a more specific classification of food products, grouping together items with similar characteristics. For example, the typology "meat" includes beef, chicken, pork, etc. The typologies in the database are: 1) fruits 2) vegetables 3) starch-based products 4) nuts, dried fruits and olives 5) pulses 6) dairy 7) eggs 8) meat 9) fish and seafood 10) oils and fats 11) sweets and chocolates 12) pastry/cakes/biscuits/ready meals.

2.1.3. Item

The item is the most detailed level of classification, corresponding to the common market terms (e.g. banana, potato, pilchard). This detailed information is essential for food impact analysis and dietary assessments.

2.2. Step 2. Food origin and domestic production

To initiate the calculation of the WF of food products, it was necessary to identify the total quantities of each food item exported from and imported into the region, expressed in metric tons. The imported volumes were recorded in descending order, accompanied by the corresponding countries of origin. To ensure the representativeness of the data, the cumulative total of these imports had to represent at least 70 % of the total import volume. The necessary data were obtained from the Datacomex database ([Ministerio de Economía, 2023](#)), a source of comprehensive statistics on the international trade of goods in Spain and the European Union. The necessary data were obtained by accessing the "dynamic reports" section and applying search criteria focusing on "Taric product codes", the year 2022 (or the most recent year available) and a historical breakdown by country. Additional reference materials were consulted to improve the accuracy of searches in the "Taric nomenclature" and to facilitate the identification of specific foodstuffs ([European Commission, 2021](#)).

The quantities of each food item produced domestically were calculated using data from the National Statistics Institute ([INE, 2022](#)), the Ministry of Agriculture, Fisheries, and Food ([Ministry of Agriculture, 2023b](#)), FAOSTAT ([FAO, 2019](#)), and the National Association of the Meat Industry of Spain. Of these sources, data from the National Statistics Institute and the Ministry of Agriculture, Fisheries and Food were considered the most reliable as they represent official national statistics that have been validated and provide comprehensive coverage. Data

from FAOSTAT was also considered highly reliable, although it incorporates international estimates that may differ slightly due to variations in global agricultural practices. Data from the National Association of the Meat Industry of Spain pertains specifically to the meat sector and was used for products within that category.

Whenever possible, data from 2022 were prioritized for estimating national production, in alignment with the import and export data used in this study. However, in cases where 2022 data were not available, data from previous years were utilized to maintain the continuity and accuracy of the estimates.

The estimation of average ratios corresponding to food imported (% Abroad) and nationally produced available for consumption (% National) was made in accordance with the formulas set forth in Eqs. (1) and (2).

$$\%National = \frac{Domestic\ production - Total\ export}{Total\ import + (Domestic\ production - Total\ export)} \cdot 100 \quad (1)$$

$$\%Abroad = \frac{Total\ import}{Total\ import + (Domestic\ production - Total\ export)} \cdot 100 \quad (2)$$

Where total import, total export and domestic production represents the total volume (in tons) of a food item imported, exported and nationally produced.

2.3. Step 3. Quantifying domestic and imported water footprints of each food item

The WF of a food product is the total volume of freshwater used throughout its production process, from farm to table. This includes water used for irrigation, livestock, processing, packaging, and transportation. In order to calculate the total WF for each product, it was first necessary to determine the proportion of domestic and imported components. The Mekonnen and Hoekstra (2010, 2011) database was employed, which provides data on the green, blue and grey WFs of a range of agricultural and animal products at the country, and even regional levels. This database remains the most comprehensive, methodologically robust, and internationally harmonized source of product-specific WF data currently available. Its continued widespread use in the scientific literature further supports its relevance and reliability (Vanham et al., 2021; González-Martínez et al., 2024; Bordoni, 2023). The WFs have been updated to the year 2022 using the fast-track method, originally introduced and substantiated by Tuninetti et al. (2017), and previously employed by Tamea et al. (2020). The fast-track method calculates the unit WF by adjusting a fixed reference evapotranspiration value according to the annual variability of product yield. Yield time-series data at the country level were obtained from the FAOSTAT database for primary crops (kg/ha), animal products (kg/animal) and derived products, where they are freely available. For derived products, the primary crop yield was used as the basis for calculations, as indicated Tamea et al. (2020). The WFs of final consumer products were aggregated without the risk of double counting because the water used in each process was exclusively attributed to one final product. When a process contributes to multiple final products, its WF was allocated appropriately among them (Aldaya et al., 2012).

For imported products, the main exporting countries were identified. The database provided WF values for these products from each of these countries in relative units (m³/t). A weighted average of these values (WF_{imported}) was calculated based on the proportion of imports from each country following the Eq. (3).

$$WF_{imported} = \sum_{c=1}^n (WF_{c,F} \cdot R_{c,F}) \quad (3)$$

- $WF_{imported}$ (in m³/t) represents the total imported WF for food item F.
- $WF_{c,F}$ (in m³/t) is the WF of the foodstuff F for country c, based on data taken from Mekonnen and Hoekstra (2010, 2011) and updated to 2022 using the fast-track method.
- n is the number of selected representative importing countries (those that supply more than 70 % of the total volume of imports)
- $R_{c,F}$ is the recalculated import ratio for country c, considering only the selected importing countries.

At the same time, the WF for domestically produced quantities of the same product (national WF) was obtained from the same database (WF_{national}) and updated to 2022 using the fast-track method. By combining the weighted import WF with the national WF, the total WF of the food product was calculated in Step 4.

2.4. Step 4. Total water footprints calculation of the food product

Finally, the green, blue and grey WFs (in m³/t) per each food product and dietary choice were estimated using Eq. (4).

$$WF_{component} = (\%national \cdot WF_{national} + \%import \cdot WF_{import}) / 100 \quad (4)$$

Where component can be green, blue or grey and expressed in m³/t. On the other hand, % national and % import, were estimated according to Eqs. (1) and (2).

For compound or prepared foods, the WF was calculated by averaging the WFs of the individual ingredients. The total WF is the sum of these components (Eq. (5)). Fig. 1 provides a summary of the principal stages involved in the development of the Spanish WF database of food commodities.

$$WF_{total} = WF_{green} + WF_{blue} + WF_{grey} \quad (5)$$

Following this step, statistical analyses were performed to characterize the variability and distribution of WFs across different food

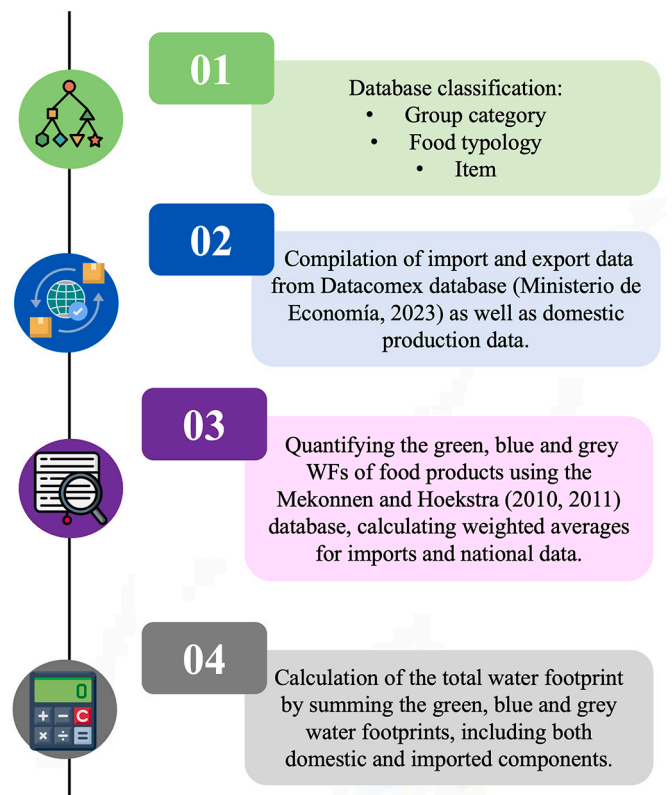


Fig. 1. Methodology for constructing the Spanish water footprint database of food commodities.

categories. Table 1 presents the results of these analyses, including key statistical measures (e.g. mean, median, minimum and maximum) for the analyzed food categories.

3. Results and discussion

3.1. Fruits

A significant variation in the total WF was observed across different fruits as can be seen in Fig. 2. Pineapple (82 m³/t), watermelon (111 m³/t) and strawberry (148 m³/t) showed relatively low WFs. Conversely, dates (2351 m³/t), cherries (2972 m³/t), and figs. (3954 m³/t) had substantially higher WFs. Furthermore, a notable discrepancy was observed in the types of water utilized in fruit cultivation (see **Supplementary dataset**). Fruits such as dates and raspberries demonstrated a markedly high blue WF (1605 m³/t and 751 m³/t, respectively), indicative of a substantial reliance on irrigation. On the other hand, the green WF was elevated for fruits like figs. (2018 m³/t) and cherries (1551 m³/t), signifying a pronounced dependence on rainfall. The grey WF generally tended to be lower, suggesting that the volume of water necessary to dilute pollutants is relatively modest for most fruits.

Cherries and figs, primarily cultivated domestically in Spain, exert significant pressure on local water resources. For instance, cherries, with nearly 70 % of national production concentrated in Extremadura and Aragon, rely entirely on Spanish water sources (Iglesias et al., 2023). Similarly, figs, with a domestic production of 3913 m³/t out of 3954 m³/t, are predominantly cultivated in Spain, particularly in Extremadura, which leads both in cultivation area and production.

On the other hand, the importation of fruits like dates (2351 m³/t), raspberries (1334 m³/t), and custard apples (1382 m³/t), shifts the environmental burden to exporting countries. Dates predominantly originate from Tunisia and Algeria, while raspberries are imported predominantly from Morocco, and custard apples from Colombia and Ecuador. The Maghreb region, encompassing Morocco, Algeria and Tunisia, is characterized by an arid to semi-arid climate and faces severe water stress due to factors such as population growth, climate change and anthropogenic contamination. Water scarcity is a critical issue in these countries, with water availability per capita falling below 1000 m³ annually (Belhassan, 2022). The cultivation of water-intensive crops such as dates and raspberries in these already water-scarce regions exacerbates local water issues, contributing to environmental degradation and reduced water availability for communities.

3.2. Vegetables

Fig. 2 presents a comprehensive analysis of water consumption in vegetable production. Asparagus emerged as the most water-intensive vegetable, with a total WF of 2281 m³/t, primarily attributed to domestic consumption (1965 m³/t out of total). Garlic and artichoke also had significant total WFs (530 m³/t and 613 m³/t respectively),

predominantly stemming from local water sources. Vegetables like collard greens (285 m³/t), broccoli (305 m³/t), swiss chard (170 m³/t), cabbage (285 m³/t) and carrots (191 m³/t) relied exclusively on domestic water for cultivation. Despite their dependence on local water sources, these vegetables have varying water consumption patterns as can be seen in **Supplementary dataset**. Blue water was the dominant component for collard greens (113 m³/t), broccoli (121 m³/t), asparagus (1144 m³/t), cabbage (113 m³/t) and carrots (95 m³/t), indicating substantial irrigation requirements. Conversely, green water was the predominant component for artichoke (330 m³/t), swiss chard (81 m³/t) and garlic (240 m³/t). Notably, garlic also exhibited a significant grey WF (152 m³/t) in addition to its green water consumption.

The globalized food system introduces complexities to these water consumption patterns. While many vegetables are primarily produced domestically, the imported WF reveals a significant burden on importing nations. Asparagus and lamb's lettuce had the highest imported WFs, 316 m³/t and 232 m³/t, respectively, with Peru as the primary source for asparagus and European countries such as Belgium, Italy and France as main suppliers from lamb's lettuce. Endive (112 m³/t), leek (117 m³/t) and radish (104 m³/t) also contributed to water consumption in importing countries, with Belgium and the Netherlands as primary suppliers for endive, Belgium and France for leek, and the Netherlands and Italy for radish. Notably, endive and lamb's lettuce are exclusively imported, placing the entire water consumption burden on other European nations.

European countries, major exporters of these vegetables, face varying water stress levels. The Water Exploitation Index Plus (WEI+) provides a quantitative assessment of water stress, revealing stark disparities across Europe. Southern European nations, such as Italy, which exports radishes, experience severe water scarcity, with WEI+ values reaching 57 %. These regions are particularly vulnerable due to the combined pressures of agriculture, public water supply and tourism, especially during peak summer periods. In contrast, Belgium and the Netherlands, have lower WEI+ values of 13.2 % and 6.3 % respectively, but still face significant water-related challenges (EEA, 2023). Belgium, which exports lamb's lettuce, endive and leeks, grapples with extreme water stress caused by high runoff, inadequate water retention, pollution and recent flooding events (EU, 2024). The Netherlands, a key exporter of radishes, despite advanced water management infrastructure, is confronted with the impacts of climate change (Toreti et al., 2022).

3.3. Starch-based products

Among cereals, wheat bran, emerged as the most water-efficient option, with a moderate total WF of 1803 m³/t as can be seen in Fig. 5. This cereal primarily relied on green water (1459 m³/t) with minimal blue water usage (58 m³/t) and a relatively significant grey WF (286 m³/t). Its production was largely self-sufficient, with minimal reliance on imports, indicating a sustainable and locally supported WF.

Table 1
Statistical measures for the food typologies analyzed in this study.

	Median	Mean	Stdev	Min	Max	Q1	Q3	CV	IQR	n
Fruits	658	903	876	82	3954	430	1144	1.0	714	28
Vegetables	176	280	414	15	2281	116	285	1.5	169	28
Starch-based products	1821	2142	1245	161	4594	1352	2910	0.6	1558	20
Nuts, dried fruits and olives	6585	7963	6293	1532	23,321	2876	11,650	0.8	8774	17
Pulses	4340	4003	3602	245	7424	245	7424	0.9	7180	3
Dairy	2626	3467	2169	1433	8050	1701	5306	0.6	3605	16
Eggs	3620	3620	3620	3620	–	–	–	–	–	–
Meat	6758	9090	8701	869	36,904	2959	12,603	1.0	9644	18
Fish and seafood	0	567	935	0	2200	0	1450	1.7	1450	9
Oils and fats	4978	8052	7209	3493	18,759	3641	15,536	0.9	11,895	4
Sweets and chocolates	1572	7459	8196	1323	16,416	1446	16,416	1.1	14,970	5
Pastry, cakes, biscuits and ready-meals	3038	2983	1202	1532	4771	1814	4090	0.4	2276	9

CV: Coefficient of variation, IQR: Interquartile Range, Q1: Quartile 1, Q3: Quartile 3, n: sample size.

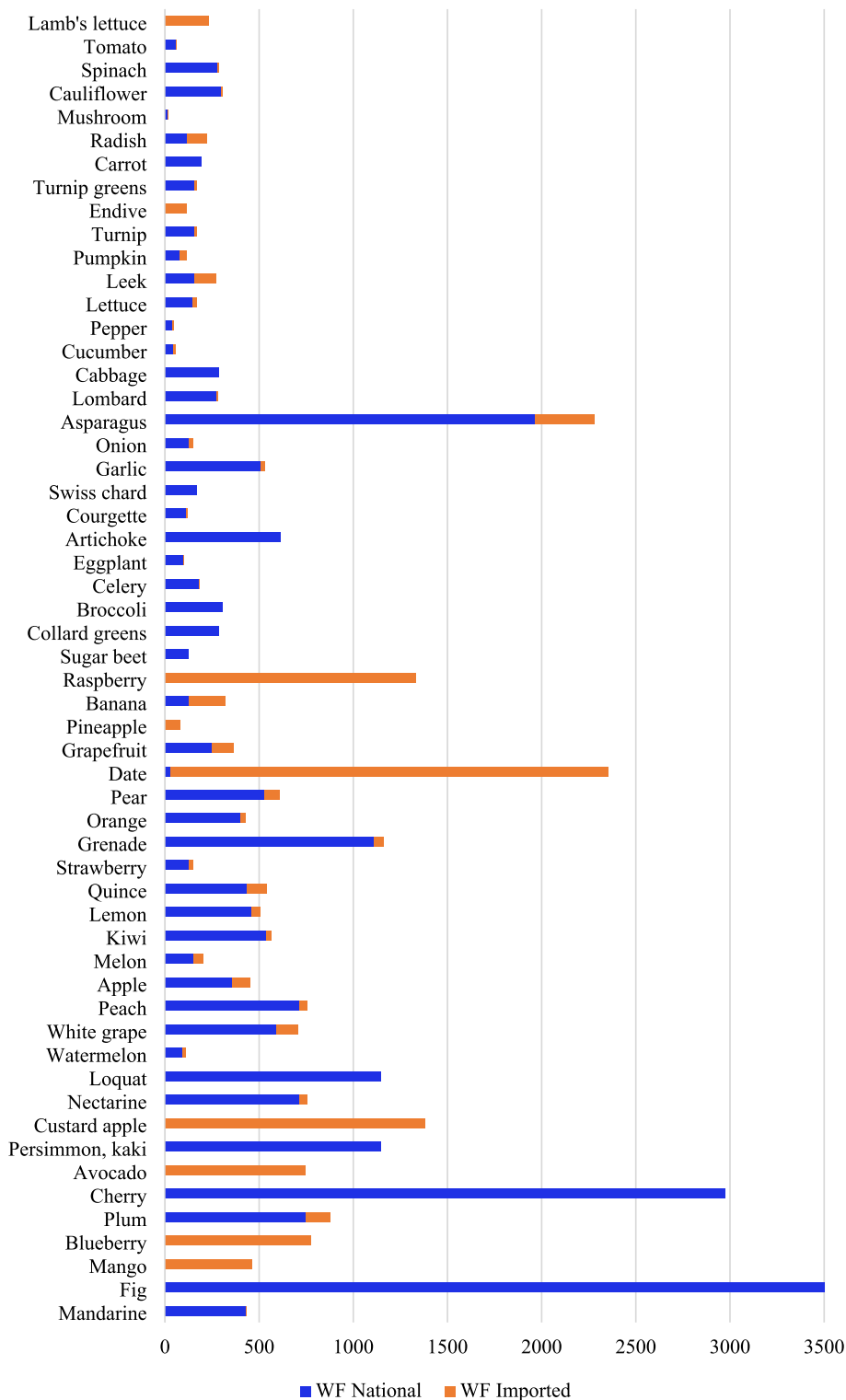


Fig. 2. Water footprint (m³/t) of crops, fresh or minimally processed plant products – Fruits and vegetables.

Oat also presented a balanced water profile with a total WF of 3103 m³/t. Although it had a significant green WF (1401 m³/t), a high blue water usage (1343 m³/t), its large grey water component (359 m³/t) suggest potential concerns about pollution. However, oats were predominantly sourced nationally (3050 m³/t) with minimal imports (54 m³/t), reflecting a strong domestic production system that mitigates external dependencies. Rice exhibited a total WF of 2291 m³/t, driven by its significant blue water usage (1157 m³/t) due to irrigation needs, along

with a substantial green WF (1080 m³/t) and a smaller grey component (54 m³/t). This high WF is compounded by substantial import reliance (1261 m³/t) compared to national production (1029 m³/t). Rice's extensive water requirements and dependency on international sources, particularly from Myanmar, Argentina, Pakistan and Uruguay, underscore its environmental and resource inefficiencies compared to the more balanced profiles of oats and wheat bran.

An analysis of bread products reveals significant variations in WF

and production systems. Oat bread stand out with the highest total WF of 3401 m³/t, all produced domestically. Its water use was notably high across all categories, with a substantial balance between green (1512 m³/t) and blue WF (1497 m³/t). In contrast, rye bread had a total WF of 1838 m³/t, heavily reliance on imports (559 m³/t) from Russia, Ukraine and Latvia. Its WF was predominantly green (1610 m³/t), reflecting a dependence on rain-fed resources with minimal blue water use (14 m³/t). While irrigation needs were low, pollution levels were moderate, as indicated by a grey WF of 214 m³/t. White bread presented a lower total WF of 1567 m³/t, benefiting from almost entirely domestic production (1563 m³/t). It is characterized by a significantly green WF (1269 m³/t) compared to blue (44 m³/t) and grey (254 m³/t) components. Tin loaf, with a total WF of 1593 m³/t, demonstrated a mixed profile. While substantial domestic production accounted for 1335 m³/t, notable imports (258 m³/t) from Portugal, Germany and Italy contribute to its WF. A significant green water component (1296 m³/t) and higher grey water usage (252 m³/t) characterized this bread type, reflecting a balance between local production and external sourcing.

Regarding breakfast cereals, corn-based cereals were the most water-efficient, with a total WF of 828 m³/t, reflecting a balance use of green, blue and grey water. On the other hand, oat-based cereals had a significantly higher total WF of 4594 m³/t, largely driven by substantial reliance on green (2043 m³/t) and blue water (2022 m³/t), along with a considerably grey water component (530 m³/t). Although entirely domestically produced, their high-water consumption indicated a significant strain on Spanish water sources. Rice-based cereals with a total WF of 2331 m³/t, were marked by intense blue water usage (1816 m³/t) and a significant green water component (515 m³/t), indicating substantial irrigation demands. While domestically sourced, the high blue

water dependency raises concerns about potential water scarcity. Rice chocolate cereals exhibited the highest total WF (4590 m³/t), with a substantial reliance on both green and blue water resources. The inclusion of imported components (103 m³/t) from France underscores the impact of global supply chains on water consumption. Similarly, wheat chocolate cereals, entirely imported from France, Germany, United Kingdom and Portugal, demonstrated a large green WF (3860 m³/t) with a moderate grey water component (160 m³/t), highlighting the environmental implications of global production and transportation. Overall corn-based cereals emerged as the most sustainable option in terms of water use, while rice chocolate cereals and wheat chocolate cereals presented the highest environmental concerns.

The comparative analysis of wheat flour, maize corn flour and maize corn starch unveiled significant disparities in their WFs. Wheat flour exhibited the highest overall WF of 1781 m³/t, primarily due to its substantial reliance on green water (1445 m³/t). In contrast, maize-based products demonstrated lower WFs of 958 m³/t and 1281 m³/t for maize corn flour and starch, respectively. These products showed a more balanced profile with higher proportions of blue water, at 423 m³/t and 568 m³/t, respectively. Despite minimal imports, all three products primarily relied on domestic production.

Among other starch-based products, pasta had a total WF of 1630 m³/t, predominantly due to green WF (1368 m³/t), and a significant imported WF of 869 m³/t, primarily from Italy. In contrast, potatoes had a much lower WF of 161 m³/t, with a balanced use of green (77 m³/t), blue (46 m³/t) and grey (38 m³/t) water, and minimal imports (37 m³/t). Popcorn, with a total WF of 716 m³/t, relied on significant blue water component (161 m³/t,) but is self-sufficient with no imports. Rice pancakes exhibited a high WF of 2322 m³/t, largely driven by blue water

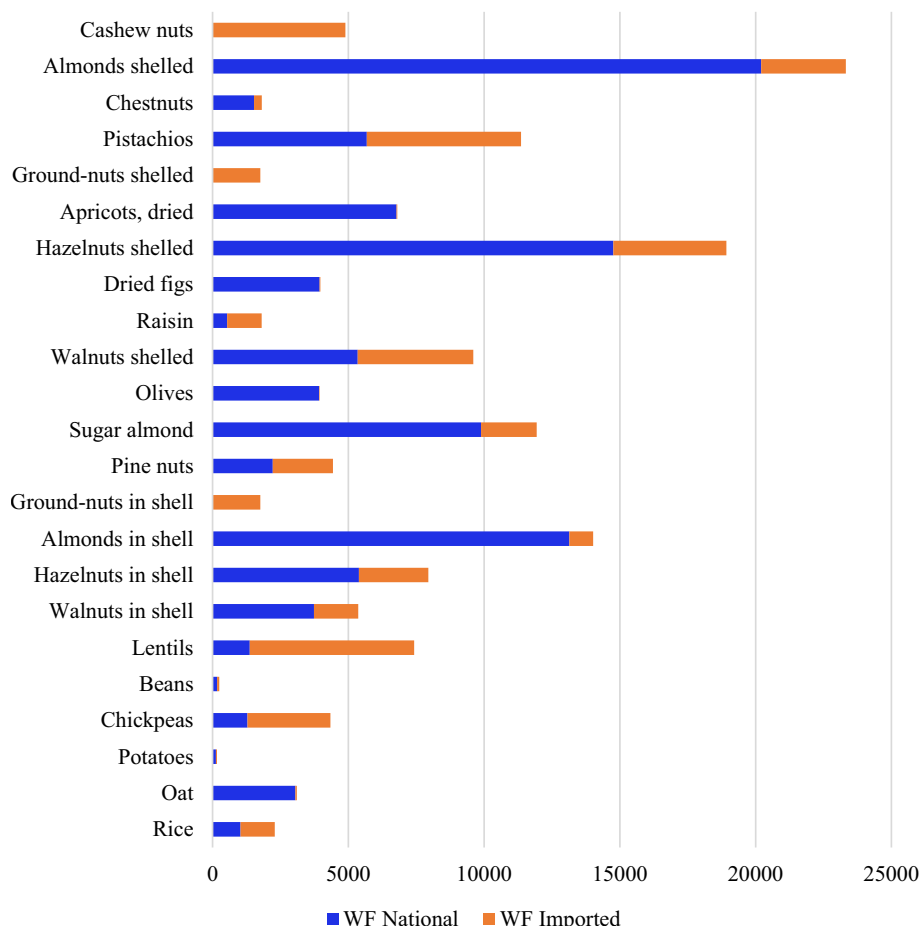


Fig. 3. Water footprint (m³/t) of crops, fresh or minimally processed plant products – Pulses, nuts, grains and potatoes.

(1789 m³/t), while couscous had a total WF of 1976 m³/t, mainly from green WF (1601 m³/t).

3.4. Nuts, dried fruits and olives

A comparison of different nuts showed that shelled almonds had the highest WF (23,321 m³/t) (see Fig. 3). In particular, shelled nuts consistently had a significantly higher WF than their in-shell counterparts. For example, shelled almonds (23,321 m³/t) had a significantly higher WF than in-shell almonds (14,017 m³/t) and similar trends were observed for walnuts, hazelnuts and peanuts. This difference was mainly due to the additional water required for the shelling process, both during cultivation and post-harvest processing.

It is important to note the geographical origin of these nuts and the associated WF. For example, cashew nuts, sourced from Vietnam and India, had a WF of 4891 m³/t. Chestnuts, on the other hand, were mainly produced domestically, with a WF of 1811 m³/t. Other nuts, such as pistachios and pine nuts, showed a combination of domestic and imported production, with about half of their WF associated with each source. It is noteworthy that pistachios presented a unique case where the blue WF (7602 m³/t) exceeded the green WF (3095 m³/t), indicating a higher reliance on surface or groundwater resources (see **Supplementary dataset**).

Dried fruits showed a considerable range in their WFs. Raisins, with the lowest WF of 1810 m³/t, showed the most efficient water use, due to specialized varieties grown in arid regions and optimized irrigation techniques. Following closely, were olives, with a WF of 3942 m³/t. Dried figs, with a WF of 3972 m³/t, had an intermediate value, influenced by their cultivation in Mediterranean climates characterized by hot, dry summers. Dried apricots, with the highest WF of 6806 m³/t, required the most water due to their larger size and the need to grow them in more humid conditions. In terms of geographical origin, raisings were mainly imported from countries with a long tradition of production, such as Turkey, while dried figs, olives and apricots were mainly grown in Spain.

3.5. Pulses

Chickpeas (4340 m³/t) and lentils (7424 m³/t) had significantly higher WFs than beans (245 m³/t). Furthermore, the national WF for beans (165 m³/t) exceeded their imported WF (79 m³/t), while the chickpeas and lentils had higher imported WFs than their national counterparts. For chickpeas, the imported WF was 3055 m³/t, while the national WF was 1285 m³/t. Similarly, lentils had an imported WF of 6056 m³/t and a national WF of 1368 m³/t. Chickpeas were mainly imported from Mexico, the United States and Canada, while lentils were mainly imported from the United States and Canada.

In terms of the distribution of WFs by type, all three products – chickpeas, lentils and beans – had higher green and grey WF than blue WFs. Specifically, chickpeas had a green WF of 2134 m³/t, a blue WF of 29 m³/t and a grey WF of 2177 m³/t. Lentils had a green WF of 2895 m³/t, a blue WF 128 m³/t of and a grey WF of 4401 m³/t. Beans had a green WF of 101 m³/t, blue WF of 57 m³/t and a grey WF of 86 m³/t.

3.6. Dairy

Whole milk exhibited the highest WF among milk products, at 2672 m³/t. In contrast, semi-skimmed and skimmed milk, with WFs of 1482 m³/t and 1435 m³/t, respectively, showed a significant reduction in water consumption due to the removal of fat. Milk powder occupied an intermediate position with a total WF of 2409 m³/t. While its domestic WF (272 m³/t) was lower than that of whole (2587 m³/t), semi-skimmed (1437 m³/t) and skimmed milk (1390 m³/t), its reliance on imports from countries such as France, the Netherlands and Germany significantly increased its overall WF due to the resource-intensive production methods prevalent in these regions. Soy milk emerged as a potentially

more sustainable alternative with a WF of 2460 m³/t. Although higher than that of skimmed and semi-skimmed milk, it represented an improvement over whole milk. However, the predominant influence on imports, primarily from France, Italy and Belgium, on soy milk's WF highlights the challenges in assessing its overall environmental performance.

The WF of cheese production was significantly influenced by several factors, including the source of the milk (cow, sheep, goat), the manufacturing process and the degree of processing. This analysis showed that sheep's milk cheeses such as Manchego (6358 m³/t) and blue cheese (7173 m³/t) and goat cheese (8050 m³/t) had the highest total WFs. Conversely, fresh cheeses such as mozzarella (1433 m³/t) or skimmed cheese (3118 m³/t) generally had lower WFs. Geographical origin also played an important role. For example, mozzarella from the Netherlands, Germany, Denmark and Belgium, camembert from France, parmesan from Italy and cheddar from Ireland, the United Kingdom, the Netherlands and Poland had a significant proportion of imported production and their entire WF was attributed to imports. This highlights the importance of considering not only local production but also global supply chains when assessing the WF of dairy products.

Additionally, other derived dairy products such as butter and yoghurt had been studied. Butter had a total WF of 5872 m³/t, with a significant contribution from domestic production at 5125 m³/t and a smaller portion attributed to imported WF at 747 m³/t. For yoghurt, the total WF was 1623 m³/t, with 1582 m³/t from national production and 40 m³/t from imports.

A consistent pattern emerged across all dairy products analyzed: the green WF, representing water from rainfall and soil moisture, significantly outweighs the blue and grey WFs (see **Supplementary dataset**). This finding underscores the critical role of rainwater in dairy production systems.

3.7. Eggs

Eggs had a total WF of 3620 m³/t, entirely sourced domestically within Spain as can be seen in Fig. 4. A breakdown of this WF revealed a green WF of 2792 m³/t, a blue WF of 354 m³/t and a grey WF of 474 m³/t.

3.8. Meat

Horse meat and bovine meat cured had the highest WFs, with horse meat (36,904 m³/t) and bovine meat cured (19,074 m³/t) leading in terms of water use. Game meat (17,645 m³/t) and pork had moderate WFs, although pork products showed significant variations depending on the specific cut. Chicken and turkey meat had the lowest WF at 2592 m³/t and 2379 m³/t, indicating the lowest water consumption compared to other meats. Goat (6135 m³/t) also had relatively low WFs. Sheep meat had a moderate WF (7422 m³/t), lower than beef and horse meat but higher than chicken and goat meat.

Within the pork category, cured products such as swine meat cured (6896 m³/t) and cured bone-in hams and cuts (6404 m³/t), as well as specific cuts such as swine cuts (6619 m³/t) or prepared hams and cuts (7091 m³/t) had higher WFs compared to offal such as liver (869 m³/t) or sausages (1549 m³/t). For all pork products, the domestic WF was significantly higher than the imported WF (see Fig. 4). In addition, the green WF dominated over the blue and grey WFs (see **Supplementary dataset**).

In the bovine category, bovine meat cured had the highest WF (19,074 m³/t), followed by bovine meat and meat offal (14,040 m³/t). Bovine cuts bone in (8726 m³/t) demonstrated a lower WF compared to bovine cuts boneless (12,124 m³/t). For all bovine products, the domestic WF significantly exceeded the imported WF, mirroring the patterns observed in pork products (see Fig. 4). Additionally, the green WF predominated over the blue and grey WFs (see **Supplementary dataset**).

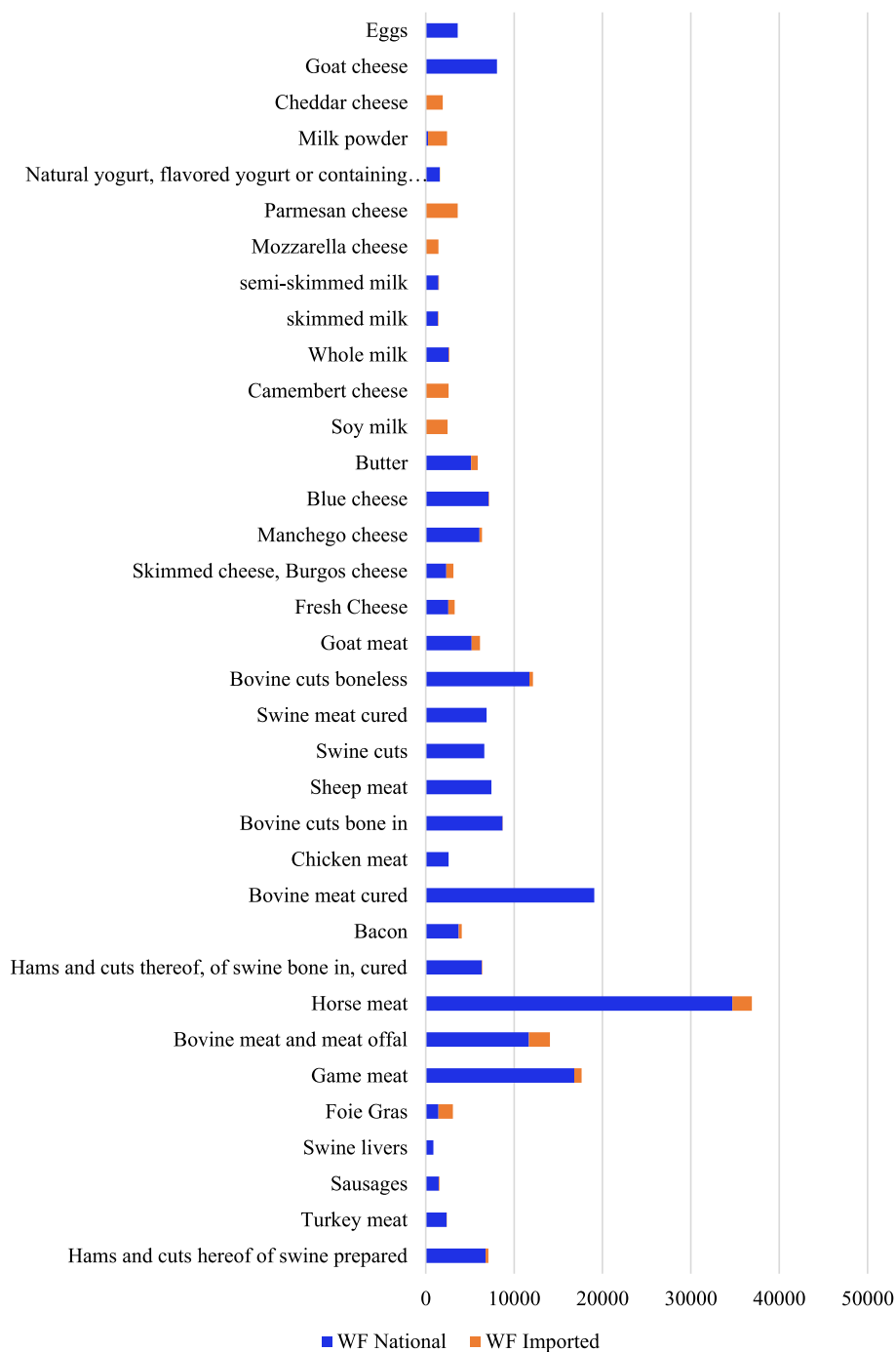


Fig. 4. Water footprint (m³/t) of animal husbandry, products of terrestrial animal origin - Meat, dairy and eggs.

3.9. Fish and seafood

For fish and seafood, the WF was estimated based on data from Pahlow et al. (2015) for aquaculture species. The WFs of salmon, cod and prawns were 2100 m³/t, 800 m³/t and 2200 m³/t, respectively. It is notable that the entire water consumption for these seafood products was attributed to domestic water sources. Wild-caught species such as hake, mackerel, pilchard, tuna, squid and mussels were excluded due to data limitations and assumed to have a zero WF.

3.10. Oils and fats

The WF analysis showed significant differences between the four

vegetable oils: olive oil, sunflower oil, palm oil and soybean oil (see Fig. 5). Olive oil had the highest total WF at 18759 m³/t, of which 18,584 m³/t came from national production. This indicates that olive oil, although deeply embedded in local agricultural systems, exerted significant pressure on domestic water resources. However, the relatively small imported WF of 175 m³/t, suggested that olive oil production was less vulnerable to global market fluctuations, making it a stable, albeit resource-intensive, option.

Sunflower oil had a relatively low WF of 5869 m³/t, significantly less than that of olive oil. The national WF accounted for 4225 m³/t, while the remaining 1644 m³/t stemmed from water resources in Ukraine, Bulgaria and the Netherlands. While this balanced reliance on domestic and international resources may appear advantageous, it also creates

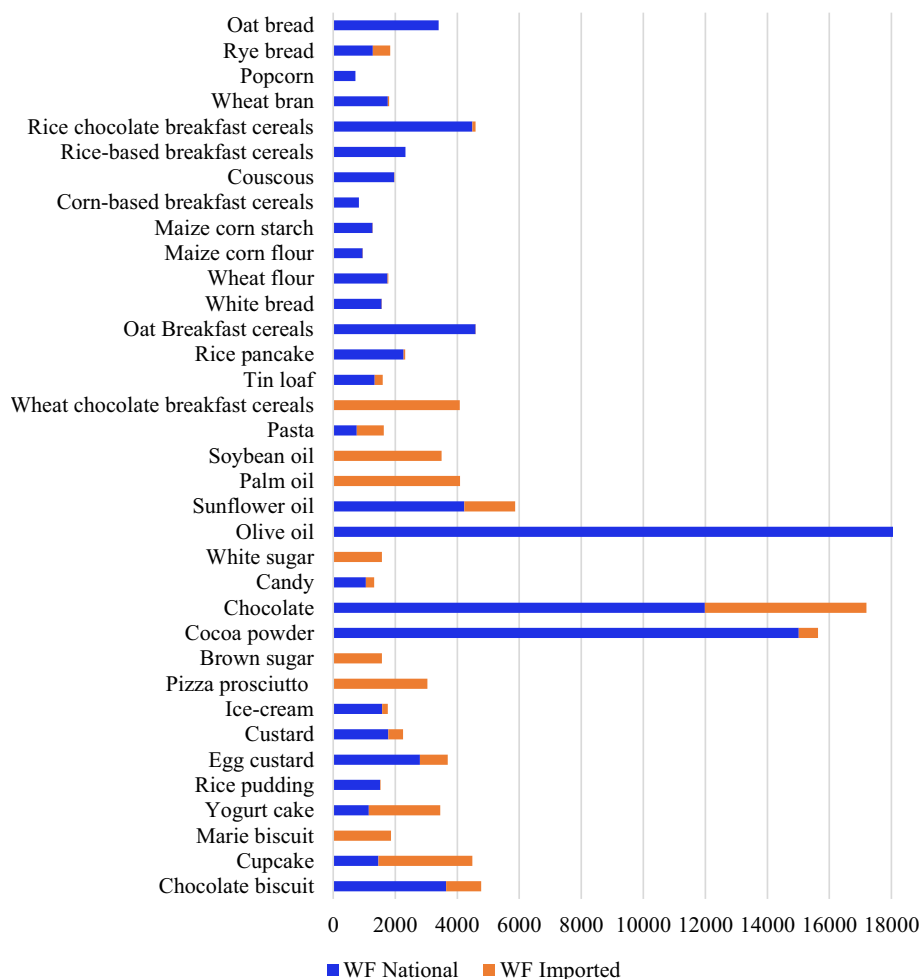


Fig. 5. Water footprint (m^3/t) of agricultural processed, mainly plant-based industrially processed foods – Oils and fats, pastry/cakes/biscuits/ready meals, starch-based products.

vulnerabilities. Disruptions in supply from key exporting countries such as Ukraine, known for its vast agricultural areas, or Bulgaria and the Netherlands, which contribute significantly to European sunflower production, could dramatically affect the availability and price of sunflower oils. This dependence highlights potential risks to environmental sustainability, particularly in regions where water is scarce.

Palm oil and soybean oil, despite having the lowest total WFs (4088 m^3/t and 3493 m^3/t , respectively) presented a distinct set of challenges. Both oils relied entirely on imported water, which reflects the externalization of their environmental impact. Indonesia was the primary source of palm oil, while Argentina and Portugal were major suppliers of soybeans. It is important to highlight that both palm and soybean oils also demonstrated significantly lower blue WFs compared to olive and sunflower oils (see [Supplementary dataset](#)).

3.11. Sweets and chocolates

The WF of brown and white sugar was comparable, with both types exhibiting a similar WF of 1572 m^3/t and 1569 m^3/t , respectively. Both types were entirely reliant on imported sugar, primarily from France and Portugal, indicating a complete absence of a domestic WF (see [Fig. 5](#)). Both brown and white sugar relied heavily on rainwater production, with moderate use of irrigation water and minimal water pollution as can be seen in [Supplementary dataset](#). Candy had a total WF of 1323 m^3/t , lower than brown and white sugars. It utilized both national (1053 m^3/t) and imported water sources (269 m^3/t), with a notable reliance on blue water (687 m^3/t), indicative of its manufacturing

processes.

Chocolate and cocoa powder were very water intensive products. Chocolate required 17,196 m^3/t , a significant proportion of which (11,986 m^3/t) was domestically sourced. Cocoa powder was slightly less water intensive at 15636 m^3/t , but relied almost exclusively on domestic water (15,011 m^3/t). Both products showed a strong dependence on rainwater (green water), with chocolate at 16805 m^3/t and cocoa powder at 15492 m^3/t , with minimal impact from blue and grey WFs.

3.12. Pastry, cakes, biscuits and ready-meals

In this category, chocolate biscuits had the highest WF at 4771 m^3/t , followed by cupcakes at 4484 m^3/t . Chocolate biscuits had much higher national WF (3638 m^3/t) than imported WF (1133 m^3/t). On the other hand, cupcakes with an imported WF of 3023 m^3/t , were largely imported from Germany, France, Italy and Portugal. Key factors driving these high WFs included the significant water use for chocolate and butter in chocolate biscuits and olive oil in cupcakes.

The products with the lowest WFs in this category were rice pudding (1532 m^3/t), ice cream (1762 m^3/t) and Maria biscuits (1866 m^3/t). Maria biscuits were entirely imported from Europe, including France, Portugal, Italy and Germany. In comparison, ice cream and rice pudding, were primarily sourced from Spain.

Yoghurt cake, egg custard, custard and frozen pizza had intermediate WFs of 3452 m^3/t , 3695 m^3/t , 2250 m^3/t and 3038 m^3/t , respectively. Yoghurt cake had a significant dependence on imported water (2301 m^3/t), mainly sourced from Germany, France, Italy and Portugal. Frozen

prosciutto pizza was imported entirely from Germany, Portugal and France. In contrast, egg custard and custard showed a higher dependence on domestic water resources, with national WFs of 2799 m³/t and 1782 m³/t, respectively.

4. Discussion of results

The findings of this study revealed both notable discrepancies and intriguing parallels when comparing the WF of food items in the Spanish dataset provided in this study with the existing literature. Particular emphasis was placed on the comparison with the SU-EATABLE LIFE database compiled by [Petersson et al. \(2021\)](#) which, unlike our study, did not incorporate grey WF values and encompassed a different temporal coverage than the dataset employed in this study. [Petersson et al. \(2021\)](#) aggregated carbon and WF values for food products based on an extensive literature review of peer-reviewed studies, public reports and Environmental Product Declarations. These values were screened using predefined criteria, standardized to ensure comparability, and aggregated into different levels of generalization ranging from specific food items to broader categories with a flag system indicating data quality and uncertainty.

Unlike the generalized, literature-based methodology employed by [Petersson et al. \(2021\)](#), our study provides a more accurate and context-specific assessment of the WF of food consumed in Spain. By integrating national-level data on consumption, trade, and production, and applying green, blue, and grey WF values based on product origin using country-specific data from [Mekonnen and Hoekstra \(2010, 2011\)](#), the approach ensures enhanced precision, transparency, and relevance. As such, it offers a more robust foundation for national environmental assessments and policy development.

4.1. Fruits

[Petersson et al. \(2021\)](#) reported an average WF of 1128 m³/t for fruit, while the Spanish dataset showed a lower average of 903 m³/t. This difference could be attributed to factors such as fruit type considered in both datasets, agricultural practices or environmental conditions specific to Spain. The median WF in the Spanish dataset (658 m³/t) was lower than that reported by [Petersson et al. \(2021\)](#) (748 m³/t). This suggests that most of the fruits analyzed in the Spanish dataset had a lower WF compared to the overall average in the study by [Petersson et al. \(2021\)](#). For example, bananas had a WF of 469 m³/t in the [Petersson et al. \(2021\)](#) study and 322 m³/t in the Spanish database. Apples were reported as 680 m³/t in the [Petersson et al. \(2021\)](#) dataset and 452 m³/t in the Spanish database. Oranges showed a WF of 654 m³/t in the [Petersson et al. \(2021\)](#) dataset compared to 428 m³/t in the Spanish database.

However, when comparing these values to other databases, such as [Frankowska et al. \(2019a, 2019b\)](#), the Spanish values were higher. [Frankowska et al. \(2019a, 2019b\)](#) estimated the WF for fresh oranges at 83 l_{eq}/kg, bananas at 4 l_{eq}/kg and apples at 32 l_{eq}/kg. These discrepancies may be due to different calculation methods, local conditions or date sources. Moreover, [Petersson et al. \(2021\)](#) omitted dates, which according to the Spanish dataset, had one of the highest WF among fruits (2351 m³/t).

Both [Petersson et al. \(2021\)](#) and the Spanish dataset demonstrated similar variability as measured by standard deviation (911 m³/t for [Petersson et al. \(2021\)](#) and 876 m³/t for the Spanish dataset). However, the coefficient of variation was slightly higher for the Spanish dataset (1.0 versus 0.8), indicating greater relative variability in the WF for different fruits or growing conditions within the Spanish dataset. In addition, the interquartile range was narrowed in the Spanish dataset (714 m³/t) compared to [Petersson et al. \(2021\)](#) (1223 m³/t), suggesting a more concentrated distribution of WFs around the median within the Spanish dataset. [Table 1](#) displays the statistical measures for the fruit category and all other food categories analyzed in this study.

4.2. Vegetables

The average WF of vegetables in the study by [Petersson et al. \(2021\)](#) was higher (443 m³/t) than in the Spanish dataset (280 m³/t). Additionally, both datasets identified asparagus as the vegetable with the highest WF, with the Spanish dataset reporting a slightly higher value (2281 m³/t) than [Petersson et al. \(2021\)](#) (2150 m³/t). This finding is also consistent with [Frankowska et al. \(2019b\)](#), which also identified asparagus as the vegetable with the highest WF in the United Kingdom.

The median WF for vegetables in the study by [Petersson et al. \(2021\)](#) was markedly higher than that observed in the Spanish dataset, at 336 m³/t compared to 176 m³/t, respectively. This suggests that a significant portion of the vegetables analyzed in [Petersson et al. \(2021\)](#) required more water, potentially due to factors such as regional differences, cultivar differences, agricultural practices, data collection methodology or data analysis methods. For example, tomatoes had an average WF of 69 m³/t in [Petersson et al. \(2021\)](#) database and 61 m³/t in the Spanish database. However, the value provided in this study was significantly lower than the one estimated by [Chico et al. \(2010\)](#) for Spanish tomatoes (236 m³/t). In the same line, onions had a WF of 290 m³/t in [Petersson et al. \(2021\)](#) database and 148 m³/t in the Spanish database. In contrast, [Mialyk et al. \(2024\)](#) estimated the WF of onions in 180 m³/t, although their study did not include grey WF.

The standard deviation vegetables was found to be similar in both studies, with a value of 393 m³/t in [Petersson et al. \(2021\)](#) and 414 m³/t in the Spanish dataset. Moreover, the study by [Petersson et al. \(2021\)](#) showed an interquartile range (153 m³/t) similar to the Spanish dataset (169 m³/t).

4.3. Starch-based products

A comparative analysis of the WFs of starch-based crops, including potatoes and rice, could be conducted within this category. In the Spanish database, the estimated WF for potatoes was 161 m³/t, a value that was lower than those reported in other studies conducted in different regions. In contrast, [Petersson et al. \(2021\)](#) estimated an average WF of 555 m³/t for potatoes, while [Rodriguez et al. \(2015\)](#) estimated 324 m³/t for potatoes in Argentina. With regard to rice, the Spanish value (2291 m³/t) was considerably higher than the global value reported by [Petersson et al. \(2021\)](#) (1651 m³/t) and, than the combined green and blue WF of this crop reported by [Mialyk et al. \(2024\)](#) (946 m³/t).

In the Spanish database, four varieties of bread were included: tin loaf, white bread, rye bread and oat bread. The WF values for these varieties ranged from 1567 m³/t for white bread to 3401 m³/t for oat bread. [Petersson et al. \(2021\)](#) estimated an average WF for bread at 1003 m³/t, which is lower than the values reported in this study. Similarly, [da Silva et al. \(2021\)](#) estimated the WF of processed bread in 50.6 L/1000 kcal (95 % CI 46.3–54.9). For pasta, the Spanish dataset estimated a WF of 1630 m³/t, which is comparable to the values reported by [Petersson et al. \(2021\)](#) (1651 m³/t) and [Aldaya and Hoekstra \(2009\)](#) (1924 m³/t).

In the case of wheat flour and maize corn flour, [Petersson et al. \(2021\)](#) indicated WFs of 1849 m³/t and 1167 m³/t, respectively, whereas the Spanish dataset reported slightly lower values of 1781 m³/t and 958 m³/t. Regarding breakfast cereals, it was only possible to make a direct comparison of oat flakes between both databases, as they were the only cereals that were analyzed in both sources. The WF for oat flakes was reported at 2416 m³/t in [Petersson et al. \(2021\)](#) dataset, while the Spanish database indicated a higher value of 4594 m³/t. [Jeswani et al. \(2015\)](#) determined that the combined blue and green water of breakfast cereals was 1672 L per kilogram of product.

4.4. Nuts, dried fruits and olives

The comparative analysis of shelled nuts focused on almonds, pistachios and shelled walnuts as these were the only shelled nuts

presented in [Pettersson et al. \(2021\)](#) and Spanish databases. The results showed a similar trend in both databases, with shelled almonds having the highest WF, followed by pistachios and walnuts. Although there were some discrepancies in the specific values, the overall trend remained consistent between the two datasets. To illustrate, the WF for almonds shelled, pistachios and walnuts shelled were reported as 23,321 m³/t, 11,363 m³/t and 9,604 m³/t, respectively, in the Spanish dataset. In contrast, the [Pettersson et al. \(2021\)](#) database provided values of 16,095 m³/t for almonds shelled, 11,363 m³/t for pistachios, and 9,173 m³/t for walnuts shelled. Despite the discrepancies in the exact figures, these values illustrate a robust correlation between the two datasets with regard to the relative water intensity of these shelled nuts.

For nuts in shell, both the Spanish database and [Pettersson et al. \(2021\)](#) consistently ranked almonds with shell as having the highest WF, with values of 8047 m³/t in [Pettersson et al. \(2021\)](#) and 14,017 m³/t in the Spanish database. Peanuts had the lowest WF, with values of 2645 m³/t in [Pettersson et al. \(2021\)](#) and 1761 m³/t in the Spanish database. However, there were differences in the specific rankings of hazelnuts, walnuts with shell and chestnuts. For chestnuts, the WF was 2750 m³/t in [Pettersson et al. \(2021\)](#) and 1811 m³/t in the Spanish database. Hazelnuts in shell had a WF of 5258 m³/t in [Pettersson et al. \(2021\)](#) and 7948 m³/t in the Spanish database. Finally, walnuts in shell had a WF of 4918 m³/t in [Pettersson et al. \(2021\)](#) and 5367 m³/t in the Spanish database.

The specific dried fruits analyzed by [Pettersson et al. \(2021\)](#) and the Spanish database differ – with [Pettersson et al. \(2021\)](#) including dried apples, coconuts, dates and raisins, while the Spanish database focused on raisins, dried figs, and apricots – the overlapping fruit, raisins, showed the following average WFs. The Spanish database recorded an average WF value of 1810 m³/t for raisins, compared to 2433 m³/t reported by [Pettersson et al. \(2021\)](#).

4.5. Pulses

The comparison of the WF values between the Spanish dataset and [Pettersson et al. \(2021\)](#) showed some differences for chickpeas, beans and lentils. For chickpeas, the values were relatively close, with the Spanish dataset reporting 4340 m³/t and [Pettersson et al. \(2021\)](#) slightly lower with 4177 m³/t. Lentils showed a higher value in the Spanish dataset (7424 m³/t) than in [Pettersson et al. \(2021\)](#) (5874 m³/t). A significant discrepancy existed for beans, where the Spanish dataset reported a much lower WF of 245 m³/t compared to 516 m³/t in [Pettersson et al. \(2021\)](#). However, [Mialyk et al. \(2024\)](#) calculated a value for green beans that was very similar to that reported in this study (250 m³/t). These variations highlight the potential differences in data collection methods, regional factors and calculation approaches used in the different databases.

4.6. Eggs

The Spanish database indicated a WF of 3620 m³/t for eggs. This figure was found to be in close alignment with the mean WF of 3361 m³/t reported by [Pettersson et al. \(2021\)](#) in their comprehensive study of WFs with a Eurocentric prevalence.

4.7. Dairy products

A comparison of the WF data for cow milk revealed that the average and median values reported in the Spanish dataset were higher than those presented by [Pettersson et al. \(2021\)](#). The mean value in the Spanish dataset was 1863 m³/t, based on the analysis of whole milk, skimmed milk and semi-skimmed milk. This was higher than the mean value of 1237 m³/t reported by [Pettersson et al. \(2021\)](#). [Bronts et al. \(2023\)](#) established that the WF for the Spanish milk was 0.67 m³ of green water, 0.15 m³ of blue water and 0.09 m³ of grey water per kilogram of milk, which were lower than the values determined in this study. Furthermore, the median value of the Spanish dataset (1482 m³/

t) was higher than that reported by [Pettersson et al. \(2021\)](#) (1261 m³/t), thus reinforcing the aforementioned trend. Moreover, the standard deviation of 701 m³/t was considerably higher than that of 374 m³/t, indicating a greater degree of variability in WFs among the milk samples included in the Spanish dataset.

In the case of powdered milk, [Pettersson et al. \(2021\)](#) determined a mean WF of 4738 m³/t, which was higher than the 2409 m³/t estimated in the Spanish database. In the case of cheese, [Pettersson et al. \(2021\)](#) demonstrated a higher overall average (6109 m³/t) and median (5253 m³/t) in comparison to the Spanish dataset, which exhibits an average of 4169 m³/t and a median of 3259 m³/t. Although the data demonstrated a greater overall availability, as evidenced by the elevated standard deviation (3044 m³/t), which was higher than that observed in the Spanish dataset (2401 m³/t), the interquartile range was smaller (3306 m³/t) than for the Spanish dataset (4507 m³/t). This indicated that although the [Pettersson et al. \(2021\)](#) dataset had a broader overall dispersion, the variability within the central portion of the data was more concentrated in comparison to the Spanish dataset. [Grossi et al. \(2024\)](#) calculated the WF of mozzarella cheese to be 6820 m³/t with green, blue and grey WFs contributing for 59 %, 12 % and 29 %, respectively. These discrepancies observed in the WFs of dairy products could be attributed to differences in production methods, processing techniques and regional variations in water availability and usage efficiency.

4.8. Meat

A comparative analysis between the Spanish dataset and [Pettersson et al. \(2021\)](#) dataset showed strikingly similar WFs for different meat products. Horse meat had the highest WF in both datasets, with [Pettersson's](#) reporting a mean value of 50,524 m³/t and the Spanish dataset reporting 36,904 m³/t.

Beef in the study by [Pettersson et al. \(2021\)](#) showed a range of 10,943 and 23,799 m³/t, depending on bone content and curing. The Spanish database for bovine meat showed a comparable range of 8726 m³/t to 19,074 m³/t, with the highest values consistently associated with cured beef. [González-Martínez et al. \(2024\)](#) estimated the WF of Spanish Terrena de Navarra PGI beef conventionally fed, to be 13,252 l per kilogram of carcass beef.

According to [Pettersson et al. \(2021\)](#), pork meat had a WF ranging from 5378 m³/t for bone-in cuts to 6299 m³/t for boneless cuts, with cured pork at 8233 m³/t. These results were consistent with the Spanish database, which reported an average of 4786 m³/t. The minimum and maximum values in the Spanish database were 869 m³/t for swine livers and 7091 m³/t for prepared hams and pork cuts, respectively.

Conversely, poultry meat had the lowest WFs. [Pettersson et al. \(2021\)](#) reported values of 4252 m³/t for boneless poultry and 3330 m³/t for bone-in poultry. The Spanish database estimated an average of 2684 m³/t for poultry meat, with the WF of chicken being 2592 m³/t. For sheep meat, [Pettersson et al. \(2021\)](#) estimated a mean WF of 9256 m³/t for boneless cuts and 8315 m³/t for bone-in cuts. The corresponding Spanish value for sheep meat was very close at 7422 m³/t. Similarly, [Mourad et al. \(2019\)](#) illustrated a comparable trend, with increases in WF from chicken meat (2092 m³/t) to sheep (6975 m³/t) and beef (17,267 m³/t).

4.9. Oils and fats

The Spanish database and [Pettersson et al. \(2021\)](#) database both indicated a consistent ranking of vegetable oils in terms of WF, with olive oil exhibiting the highest values. While there was a slight variation in the specific values, the trend remains consistent: olive oil (18,759 m³/t and 14,416 m³/t, respectively), sunflower oil (5869 m³/t and 6792 m³/t), palm oil (4088 m³/t and 4971 m³/t) and soybean oil (3493 m³/t and 4190 m³/t). These findings indicate a robust correlation between the two datasets with regard to the relative water intensity of these oils.

4.10. Sweets and chocolates

A comparison of the WF values of sugar, chocolate, and cocoa powder between the Spanish dataset and [Pettersson et al. \(2021\)](#) dataset revealed several similarities. In the case of sugar, the average value reported by [Pettersson et al. \(2021\)](#) was 1225 m³/t, while the corresponding figures for white and brown sugar in the Spanish dataset were 1569 m³/t and 1572 m³/t, respectively. With regard to chocolate, both datasets estimated the same WF 17196 m³/t, thereby demonstrating complete alignment. Similarly, [Konstantas et al. \(2018\)](#) reported that approximately 10,000 l of water were required to produce a kilogram of chocolate. For cocoa powder, the Spanish estimation was 15,636 m³/t, which was almost identical to [Pettersson et al. \(2021\)](#) estimation of 15,618 m³/t. These comparisons highlight the strong consistency between the Spanish data and [Pettersson's](#) findings for these products.

4.11. Pastry, cakes, biscuits and ready-meals

In comparing the WF of biscuits, [Pettersson et al. \(2021\)](#) reported a value of 1684 m³/t for simple cookies and 2895 m³/t for cookies with chocolate or cream filling. In contrast, the Spanish database listed higher values, with simple cookies such as Marie biscuits at 1866 m³/t and chocolate biscuits at 4771 m³/t. With regard to cakes and croissants, [Pettersson et al. \(2021\)](#) estimated a WF of 1856 m³/t. However, the Spanish database reported significantly higher values for cupcakes (4484 m³/t) and yoghurt cake (3452 m³/t). It is important to note that the Spanish database calculated these WFs based on ingredient-specific data, which may differ from the calculation methods used in the [Pettersson et al. \(2021\)](#) study.

5. Limitations and outlook

The robustness of this study was supported by the validation of the dataset through comprehensive statistical analyses. Key metrics such as median, mean, coefficient of variation, and interquartile range across food typologies showed that the WF values capture a realistic and coherent variability consistent with known differences in agricultural water use. Although some categories exhibited higher variability or skewed distributions, the overall patterns aligned well with previous literature, confirming the reliability and relevance of the results presented.

The database used was constructed based on information available at a specific point in time, including updated trade data and the [Mekonnen and Hoekstra \(2010, 2011\)](#) dataset, which was further refined through the fast-track method ([Tuninetti et al., 2017](#)) to account for the temporal variability of the WF. This refinement helps ensure the relevance and timeliness of the data. Nevertheless, certain limitations should be considered when interpreting the results. For products such as chocolate, pasta, pistachios and candy, the WF database did not account for interannual variations due to the lack of yield data. Additionally, the analysis was conducted at the national scale and did not capture sub-national (e.g., provincial) variability, nor did it include historical time series data, which could provide valuable insights into spatial and temporal dynamics of water use. Utilizing models that incorporate higher spatial and temporal resolution would improve the accuracy and relevance of the estimates, especially for products sensitive to climatic changes.

Secondly, the study did not account for how current dietary practices or future policies might influence the WF of diets. The implementation of policies promoting more sustainable dietary patterns could play a significant role in reducing the national WF. For example, previous studies have shown that transitioning from a Paleo type diet to a Mediterranean diet could reduce the WF by approximately 13 % per person per day ([Cambeses-Franco et al., 2021](#)). Currently, Spain has the National Food Strategy, approved in 2025, which aims to establish a comprehensive, sustainable and competitive food system rooted in local

territories and based on diversity and production of healthy, accessible and high-quality of foods. However, organizations such as Greenpeace have pointed out that this strategy lacks concrete and ambitious measures to reduce the WF of the food system. In this context, future research could build upon the database developed in this study to more thoroughly assess the water sustainability of the Spanish food system, considering different scenarios of changes in public policies, consumption habits and agricultural production.

6. Conclusions

The present study offered the first comprehensive database of WF values for a diverse range of food items and food categories commonly found in the Spanish food basket. The database uniquely includes both domestic and imported WFs, as well as a detailed analysis of green, blue and grey WFs per food item. While the general patterns observed — such as lower WFs for plant-based foods and higher footprints for ruminant meat — are consistent with previous global studies, the value of this work lies in its localized application to Spain. The database thus provides a useful resource for researchers and decision-makers interested in national-level food and water policy. Moreover, it serves as a robust and flexible input for the assessment of dietary WFs, as has already demonstrated in previous studies analyzing the environmental implications of different dietary patterns in the Spanish context such as the Mediterranean Diet, the Southern European Atlantic Diet or the Spanish Dietary Guidelines ([Cambeses-Franco et al. \(2022\)](#), [González-García et al., 2022](#)).

A publicly accessible WF database represents a valuable resource for researchers, businesses, citizens and policymakers alike, facilitating the transition to sustainable food systems. The provision of essential data and encouragement of contributions serves to promote transparency and collaboration. The database enables users to comprehend the WFs of assorted foods, underscoring the necessity to provide individuals and communities with the instruments to implement sustainable practices. This approach is essential to promote behavioral change, reduce the environmental impact of diets, support the national network on water use in the food sector, improve water management in Spain and serve as a model for global initiatives.

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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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.eiar.2025.108120>.

Data availability

All data used are cited in the article

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