

How green are my apples? The greenhouse gas emissions and blue water scarcity footprint of fresh apple supply chain

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ABSTRACT

The environmental impact of the UK fresh apple supply chain depends on the sourcing locations. This paper examines the contribution of production, storage, processing, and transport to evaluate the greenhouse gas emissions (GHGE) and blue water scarcity footprint of the main sources of apple supply to the UK (2016 – 2025). Domestic production accounted for 38 % of supply, with imports from the rest of Europe (e.g. France, Italy, Germany, Ireland, The Netherlands, Spain) representing for 37 % and most of the remainder from southern hemisphere countries, such as South Africa (12 %), New Zealand (7 %) and Chile (5 %). Our results revealed that GHGE at the orchard stage for UK, European, and Chilean apples are similar. During postharvest, cold storage is the main contributor for GHGE, which were 40 % lower in northern hemisphere countries compared to maritime shipping stages for the southern hemisphere areas. Transport emissions are affected by international travel distances. South Africa and Spain presented the highest blue water consumption (BWC) as well as blue water scarcity footprint. We found that blue water scarcity footprints are negligible where apple production is rainfed. The results suggest that in order to mitigate GHGE, energy mixes need to be improved as well as cold storage technologies. For water footprint, implementing infrastructural changes is paramount. These results can help as decision making tool to define new sourcing strategies that can minimise environmental impacts. This assessment also highlights limitations in methodology, including inconsistent approaches in GHGE assessment, and underscores the need for standardised methodologies, emphasises the role of externalities, and highlights the importance of considering economic and social factors in assessing environmental trade-offs in apple supply chains.

1. Introduction

Fresh fruit and vegetables are an essential part of a healthy diet; yet, global consumption remains well below the 400 g per day target of the World Health Organisation (WHO) and the 500 g per day set by EAT-Lancet (Willett *et al.*, 2019) recommendations. In 2015, only an estimated 36 % of the global population had adequate access to available and affordable fresh products (Mason-D'Croz *et al.*, 2019). Insufficient fruit and vegetable consumption contributes to high national rates of non-communicable diseases, including cardiovascular disease, cancer, diabetes, obesity and mental health issues, imposing substantial burdens on health services and contributing to mortality (WHO, 2012). With a global growing population and increasing extreme weather events, it is critical that the production of fresh produce is able to meet growing demand in a sustainable and resilient way.

Expanding fruit and vegetable supply to improve nutrition comes

with environmental trade-offs (Mason-D'Croz *et al.*, 2019). Production, processing, transport and storage of fresh produce can generate significant greenhouse gas emissions (GHGE; Webb *et al.*, 2013; Frankowska *et al.*, 2019), impact biodiversity (Newbold *et al.*, 2015), degrade soil, and contribute to water scarcity (Hess and Sutcliffe, 2018). While our analysis treats existing supply networks and observed sourcing patterns as the empirical basis for environmental accounting, it is important to stress that these networks are not immutable. Food supply chains are themselves the product of broader patterns of trade, policy and economic incentives, together with agroclimatic and consumer requirements. However, more localised sourcing strategies may alter the balance of environmental externalities. Hence, while this paper quantifies GHGE and blue water scarcity footprints associated with observed United Kingdom (UK) apple sourcing, we emphasise that sourcing decisions are endogenous and can be shaped by policy, trade rules and retailer strategies. This framing clarifies that the observed

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environmental costs partly reflect structural features of globalised trade rather than innate properties of particular growing regions (Kummu et al., 2020; Frankowska et al., 2019).

The global fruit market is highly international: approximately 9 % of all fruit grown are traded across borders (van Rijswijk et al., 2025) and long-distance transport significantly contributes to “food-miles” emissions (Li et al., 2022). Fruit is often grown under irrigation in climate vulnerable or water stressed regions (Scheelbeek et al., 2020; Hess and Sutcliffe, 2018), meaning that simply scaling up current production to meet rising demand risks exacerbating environmental impacts, particularly GHGE and water scarcity (Stratton et al., 2021). In the UK, fruit consumption contributes ca. 3.2 Mt CO₂e GHGE and 315 Mm³ eq. water use annually, with apples ranking as the third most impactful fruit after bananas and oranges (Frankowska et al., 2019). Unlike bananas and oranges, apples can be sourced from multiple regions, creating diverse environmental outcomes.

Within the UK, domestic production can supply around 60 % of overall food demand, including grains, meat, dairy, and eggs, but only 16 % of the fruit consumed is produced locally (Department for Environment, Food and Rural Affairs [DEFRA], 2021). Apples (*Malus domestica*) are the second most supplied fruit in the UK after bananas, yet domestic production covers only about one third of fresh apples consumption, with the remainder sourced primarily from France and other western and southern European countries (DEFRA, 2020). To ensure year-round availability, European apples are stored, and supply is supplemented by imports from southern hemisphere countries, especially South Africa, New Zealand, and Chile (Hess and Sutcliffe, 2018), while the USA, once an important supplier until 2010, no longer plays a major role. This diversity in sourcing regions, production methods, transportation, and storage creates significant variation in environmental externalities.

However, there is very limited research that has quantified both GHGE and water footprints for UK apple imports using consistent metrics. Using the UK as a case study, this paper evaluates two environmental indicators, the GHGE and water scarcity, associated with different apple sourcing options. By integrating life cycle inventory data, we quantify cradle to consumption impacts and explore how trade and storage technologies influence environmental trade-offs. The findings aim to inform strategic procurement decisions and climate adaptation policies, highlighting actions to mitigate GHGE and water scarcity and supporting the sustainable sourcing of apples.

2. Methods

2.1. Scope of the study

We herein consider the externalities of 1 kg of fresh apples from cradle to delivery at a UK retailer’s regional distribution centre (RDC). Five stages can be identified with GHGE and water consumption potentially associated with each (Fig. 1). Apples destined to juices and cider were excluded from the study.

In order to carry out this study, the following assumptions were

considered:

1. The orchard stage is similar in locations of production with apples grown on trees. GHGE are particularly associated with mineral fertiliser, agrochemicals and energy/fuel use for machinery and irrigation. Almost all water consumption occurs at the orchard stage where apple trees are irrigated.
2. Local processing includes harvesting, washing and packing of apples all of which consume energy and fuel. Water is used in product washing and disinfection.
3. Some domestic and European apples are transported directly to the RDC for retail in-season. GHGE are associated with fuel for transportation.
4. Others are stored under controlled conditions until ready for retail out of season. These apples are generally kept in cold-stores combined with controlled atmosphere (CA, including dynamic CA [DCA] and ultra-low oxygen [ULO] storage) or 1-methylcyclopropene (1-MCP), both of which enable apple storage life to be extended up to 10 months after harvest (Boschiero et al., 2019; Watkins, 2008). Maintaining low temperatures has significant energy consumption and associated GHGE.
5. Apples from Europe are transported in refrigerated trucks, including a short sea/tunnel crossing of the English Channel or Irish Sea. Apples from the southern hemisphere include international shipping, typically in a refrigerated container (Fitzgerald et al., 2011). Water consumption in storage and transport is trivial comparison to the orchard stage.

The later stages of the supply chain, including distribution, retail and consumption, were considered out of scope as the potential environmental impacts are independent of the place of origin of the produce.

2.2. UK apple supply

Domestic production of apples (DEFRA, 2020) and the mass of imports and exports of fresh apples from each country was obtained from the UK Trade Info database (HM Revenue and Customs, 2022) for the years 2016 – 2025. These statistics only showed the country and not the region from which apples exported to the UK were grown, which is important when considering water scarcity. Therefore, for each country and using a range of local sources, the region that accounted for over 50 % of the country’s production was selected as representative for each country (Table S1). Where no single region dominated, several production regions were selected in order to reach the 50 % threshold. We assumed that re-exports (i.e. apples imported into a third country and re-exported to the UK) are not significant.

2.3. Greenhouse gas emissions

For GHGE, a review of literature was carried out. A scoping study of 10 papers was used as an indicative dataset to identify key search terms. Scopus was searched on 26th May 2021 with the following terms:

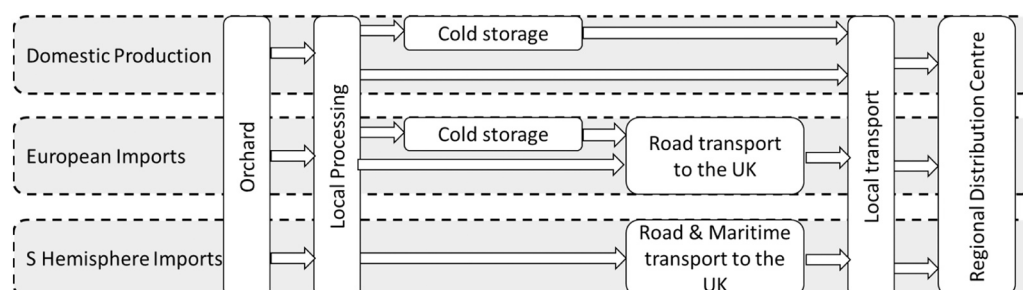


Fig. 1. Key stages of the fresh apple supply chain from orchard to a UK regional distribution centre.

((TITLE-ABS-KEY (apple) OR TITLE-ABS-KEY (malus AND domestica)) AND (TITLE-ABS-KEY (lca) OR TITLE-ABS-KEY ("lifecycle assessment") OR TITLE-ABS-KEY ("CO2 emission*") OR TITLE-ABS-KEY ("carbon footprint*") OR TITLE-ABS-KEY ("greenhouse gas emission*") OR TITLE-ABS-KEY (peu) OR TITLE-ABS-KEY ("food miles")))).

In order to restrict results to countries that supply the UK market, the filter TITLE-ABS-KEY (country) was added. No time period restrictions were considered on the search. The list of papers was refined in three stages. Firstly, all titles were reviewed and papers unrelated to the topic were excluded (for example, papers about 'apple' computing and technology, papers which included the colloquial term "apples to apples" in the title, and papers that were in a different geography). Following this first stage, 49 papers were remaining. The second stage reviewed all abstracts and excluded papers which were found to not be relevant to the topic or did not include GHGE estimates. Following this stage of refinement, 38 papers were retained for the final stage. In addition, we allowed for secondary references to be included which resulted in an additional two additional peer-reviewed papers and from four grey literature. The final stage was to extract quantitative information regarding GHGE at different stages of the apple supply chain under conventional production systems. An extra search was carried out on the 25th November 2025, following the same methodology, in order to add any additional papers that might be of interest. A total of 46 articles were found, most of them focusing on apple processing. Only one was selected for this study. Data for organic agricultural production systems were excluded. Misquoted data points were corrected through referencing the original source of the data, and normalised data was excluded. The methodology used, key assumptions, and country of origin were also recorded. Following the extraction of values from the literature, the minimum, maximum and mean values for each stage of the GHGE were calculated. The distance for transporting apples from the UK port of entry to UK RDCs was assumed to be the same for all imported apples. Therefore, an average value was calculated across all non-UK sourcing studies, since this leg of the journey occurs within the UK and does not depend on the country of origin. Where no data were available for international transport for a particular country, estimates from other countries with similar transport types were adjusted proportional to the distance travelled.

2.4. Blue water scarcity footprint

When considering the impacts of a supply chain on water resources, we considered 'green' water as rainfall used at the point at which it falls; and 'blue' water referring to water drawn from sources (such as groundwater resources), which could have otherwise been used for alternative purposes, and therefore has a greater opportunity cost (Aldaya et al., 2010). Water consumption is defined here as "water removed from, but not returned to, the same drainage basin" (ISO, 2014), as this has a higher impact on local water resources. Not all blue water that is used in the fruit supply chain is 'consumed'. For example, water used for washing the produce and then later returned to the local environment, has been used but not consumed and, subject to water quality, can be directed to alternative uses. Estimates of blue water consumption (BWC) in the orchard stage were taken from Mekonnen and Hoekstra (2011) for the key apple production regions. Small amounts of water (1–4 L/kg) are used in washing produce and disinfection (Trajer, Winiczenko and Drózd, 2021) although this is largely non-consumptive and virtual (embedded) water associated with the production of energy, fuel and packaging is trivial in comparison to the water used in the orchard stage. The water consumed post farm-gate is negligible (Hess et al., 2015) and is unlikely to vary significantly according to sourcing location and was, therefore, not included. Blue water consumed in fruit production therefore competes with other local human and ecosystem uses, but blue water consumed in a region with abundant water resources has a lesser impact than the equivalent quantity consumed in a region of high water-scarcity. Therefore, the

volume of blue water consumed can be weighted by an index of local water scarcity to obtain a blue water scarcity footprint (BWSF; Pfister, ISO, 2014) that better allows us to understand the potential impacts of water consumption on other water users and uses. A wide range of water scarcity indexes have been used to characterise water consumption based on, for example, environmental impacts (Damiani et al., 2021), planetary boundaries (Bjørn et al., 2020) or freshwater scarcity (Ridoutt and Pfister, 2010). In this study we have used the regionally applicable values of Available Water Remaining (AWARE; Boulay and Lenoir, 2020) as a method that has received consensus among the life cycle assessment (LCA) community. The BWSF of apples produced in the region, i , was calculated from,

$$BWSF_i = BWC_i AWARE_i$$

Whilst the units of the BWSF (L H₂Oeq/kg) have no physical meaning, it provides a useful metric for comparing the potential impact on water scarcity from production in different regions as it considers both the volume of water consumed and the local water scarcity.

As it is not possible to know which regions apples exported to the UK come from, for those countries where multiple producing regions were included, the BWSF for each major region was estimated and weighted according to the relative production in each region (Table S2). In summary, the BWSF was calculated using the AWARE methodology, which applies a characterisation factor (CF) to the BWC at the sub-basin level. The BWC represents the volume of surface and groundwater consumed. AWARE CFs are geographically and temporally specific, calculated based on the ratio of water availability to human demand, using monthly data for the study period (2016–2025).

3. Results

3.1. UK apple supply

Average (2016–25) supply (domestic production + imports) was ~600,000 t/year (Table S1). Domestic production accounted for 38 % (Fig. 2) with a further 37 % imported from the rest of Europe (especially France, Italy, Germany, Irish Republic, Netherlands and Spain). Southern hemisphere countries, especially South Africa (12 %), New Zealand (7 %) and Chile (5 %) are important for supply between April and September. About 3 % of the UK fresh apple supply was exported to the European Union, which we assume is all domestically grown.

3.2. Greenhouse gas emissions

A total of 19 sources were found that contained GHGE estimates for one or more stages in the supply chain of apples in the main producing countries for the UK market (Table S3), which were aggregated in our analysis. Most covered production in the UK and France. Only one paper included data for each of South Africa and Chile and there were none covering The Netherlands or the Republic of Ireland. In all, there were 65 values of GHGE for individual stages in apple production and the supply chain, but few studies contained all supply chain stages. There were 23 estimates of GHGE for the orchard stage and 15 for processing or storage, but transport and port operations were rarely included. The values were aggregated according to four stages of production by region (Table 1). The transport to processing site, processing and storage stages were aggregated, given few studies separated these stages. For UK production, domestic transport to processing site was taken as the average of other reported values (0.004 kg CO₂e/kg) as this was not considered in any of the studies. For southern hemisphere supplies, transport to the port, national port operations, international transport and UK port operations were aggregated. In summary, the total GHGE to the RDC in the UK are similar for UK, European and Chilean apples ~0.44 kg CO₂e/kg. Emissions at the orchard stage were not significantly different between UK, Europe or southern hemisphere production.

Audsley et al. (2010) only presented a total value for the supply chain

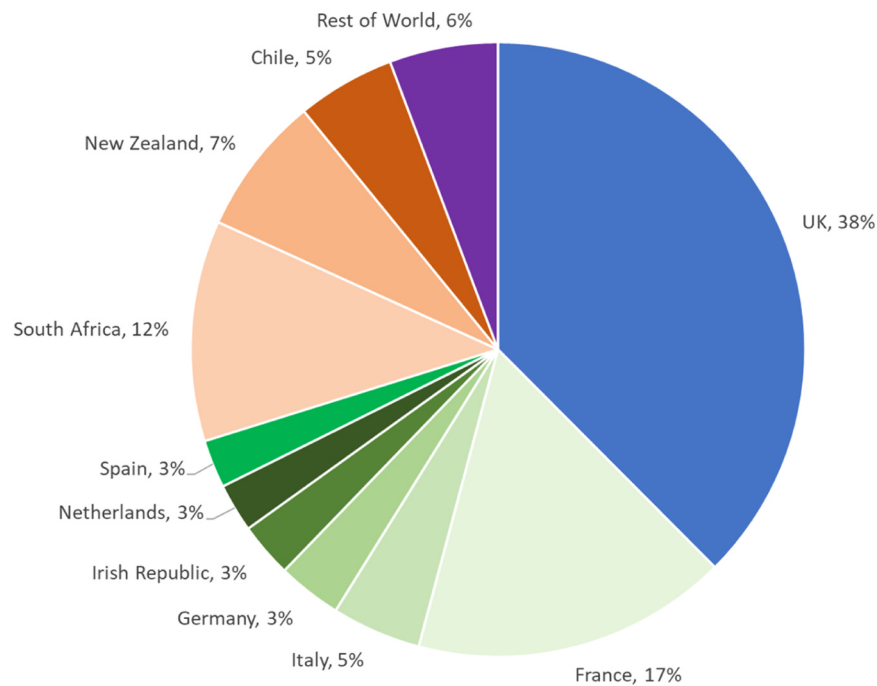


Fig. 2. Source of apples by weight supplied to the United Kingdom (UK) market (2016 – 2025).

Table 1

Average greenhouse gas emission (GHGE; kg CO₂e/kg) by reported stage for apple production and the supply chain by region of production considering United Kingdom (UK), Europe, New Zealand (NZ), South Africa (SA) and Chile. Maxima and minima ranges are given in brackets where available.

Stage	UK	Europe	NZ	SA	Chile
Orchard	0.179 (0.150 – 0.200)	0.100 (0.032 – 0.207)	0.067 (0.04 – 0.100)	0.275 (0.270 – 0.280)	0.064 (-)
Processing and storage	0.229 (0.090 – 0.200)	0.213 (0.165 – 0.262)	0.084 (0.063 – 0.100)	0.771 (0.749 – 0.790)	0.090 (-)
International transport	N/A	0.097 (-)	0.505 (0.125 – 0.881)	0.246 (-)	0.249 (-)
UK transport to RDC	0.037 (0.003 – 0.098)	0.037 (-)	0.037 (0.003 – 0.081)	0.037 (-)	0.037 (-)
Total	0.445	0.447	0.693	1.328	0.440

which was not included in the comparisons shown in Table 1. Their values of for the UK (0.32 kgCO₂e/kg), France (0.43 kgCO₂e/kg) and New Zealand (0.88 kgCO₂e/kg) were broadly in line with findings.

3.3. Blue water scarcity footprint

South Africa and Spain showed the highest BWC compared to the rest of producing countries as well as the highest blue water scarcity footprint due to the higher AWARE index values (Table 2). Apple production in UK, Germany, Italy, Netherlands, New Zealand and Ireland have similar and negligible blue WSFs as the majority of apple production is rainfed and in regions of low water scarcity. France has a larger WSF (464 L H₂Oeq/kg); however South Africa and Spain have WSFs > 10,000 L H₂Oeq/kg. Apples from the western Cape (South Africa) have the largest WSF due to the combination of a large BWC (large irrigation volume) and high AWARE index (water scarcity). Although the Maule region (Chile) is the most water scarce of regions exporting to the UK and has the highest AWARE index, the BWC per kg is lower than in Western Cape and the overall WSF is therefore lower.

Table 2

Blue water consumption (m³/t), water stress index and blue water scarcity footprint (L H₂Oeq/kg) for the key apple production regions in the UK supply chain.

Country	Regions	Blue water consumption (m ³ /t)	AWARE Index	Blue water scarcity footprint(L H ₂ Oeq/kg)
Chile	Maule	75	88.2	6615
France	Provence-Alpes-Côte d'Azur, Midi-Pyrénées, Pays de le Loire	49	11.08	464
Germany	Altes Land, Bodensee	1	1.72	2
Italy	Trentino Alto Adige	0	0.90	0
Netherlands	Central	2	1.46	3
New Zealand	Hawkes Bay	0	1.0	0
Republic of Ireland	Dublin, Kilkenny, Tipperary, Waterford	0	1.47	0
South Africa	Western Cape	153	73.3	11,215
Spain	Catalonia	127	84.50	10,732
UK	South-East	5	3.48	17

4. Discussion

4.1. Cold storage: a key contributor to greenhouse gas emissions

Cold storage contributed 36 % and 41 % to the mean UK and France GHGE values respectively. UK apples were typically stored at 0.5 – 2°C, although some varieties (e.g. cv. “Bramley”) may be stored up to 5°C, or under ambient temperatures for short-term storage. Historically only 20 – 30 % of fruit would be stored beyond January – March, but increasing proportions of fruit are now stored for up to 12 months to target peak pricing periods, increasing the contribution from storage. Storage at a low temperature, generally combined with CA (including DCA and ULO storage) and 1-MCP, both of which enable apple storage life to be

extended up to 10 months after harvest (Boschiero et al., 2019; Watkins, 2008). CA use is commonplace, but is generally reserved for crops destined for long-term storage, although DCA has not yet become industry standard due to cost/infrastructure limitations. Accurate quantification of postharvest storage is generally absent from existing literature, with estimates ranging from 0.036 to 0.450 kg CO₂e/kg (de Kock et al., 2019; Iriarte et al., 2021). These results were in line with the previous finding, which highlighted that cold storage and packaging of apples were the main contributors to GHGE and energy demand (Boschiero et al., 2019). Postharvest storage impacts are unlikely to vary significantly between origins, but instead will reflect systemic and methodological differences during quantification and this should be addressed in further analysis. However, the mean GHGE attributed to cold storage for northern hemisphere countries was at least 40 % lower than that attributed to the maritime shipping stages for the southern hemisphere countries. Values for New Zealand and South Africa are higher due to international travel (although there was a wide range of values provided for the maritime shipping stage of New Zealand produce, with the maximum value of 0.881 kg CO₂e/kg (Rizet et al., 2012) seven times larger than the minimum value of 0.125 kg CO₂e/kg (Saunders and Barber, 2017; Mason et al., 2002). Transport from Chile was less than 50 % of the average GHGE from New Zealand (Iriarte et al., 2021) corresponding with a 25–50 % shorter transport distance. Differences in the GHGE of the agricultural and processing stages between sourcing locations can be partly attributed to a country's energy mix, as higher proportions of fossil fuels result in higher GHGE attributed to energy usage (Ray and De, 2020). South Africa has the highest proportion of fossil fuels in its energy mix and this may partly account for the high GHGE. Differences in the GHGE of the agricultural and processing stages can also be partly attributed to yield. UK customer demand has increased for newer varieties such as cvs. “Jazz” and “Pink Lady”, which are less suited to the UK climate compared with older varieties leading to yield reductions, although improvements have been made through improved clonal selection in recent years. Substantial differences are reported for GHGE during orchard production between UK/EU and South Africa, and New Zealand/Chile. Reported yields for New Zealand and Chile were double that of UK orchards (Saunders and Barber, 2017; Iriarte et al., 2021), contributing to the sizable difference

in GHGE per kg between regions. This finding was of particular importance in the UK and South Africa, the two countries found to have the highest impacts at agricultural stage and the two countries with the lowest typical yields. Total GHGE emissions per ha were comparable between the UK and New Zealand once the influence of the yield discrepancy (Saunders and Barber, 2017), indicating that the primary driver of the discrepancy in reported GHGE emissions between regions is due to comparatively low yields in UK/EU against a background of relatively standardised production methods. Increasing orchard productivity may reduce total GHGE per kg due to distribution of impacts across a wider quantity of produce. However, intervention strategies which increase yield outputs may introduce additional environmental impacts which must be reconciled against yield benefits. For example, the use of netting to aid pest management can enhance yields but is liable to substantially increase total GHGE through increased plastic and metal use (Boschiero et al., 2018) Fig. 3.

Few studies in the systematic review included values for the road transportation and cold storage, leading to a higher level of uncertainty for these stages of the supply chain. There were also few values provided for the South African and Chilean GHGE, as each of these countries of origin had only one paper included in the literature review. This leads to a high level of uncertainty and greater influence of methodological differences, particularly when comparing with countries of origin with a more substantial body of research, therefore additional studies of apple production in these two geographies would be of great value. This is also reflected in the considerable discrepancy in GHGE estimates for cold storage and processing, and is predominately due to paucity of data surrounding energy consumption during storage. de Kock et al. (2019) estimates of electricity consumption during cold storage were 4–12x that of values utilised by Saunders and Barber (2017). More accurate assessment of postharvest energy demand and GHGE is necessary to reduce the impact of such methodological differences.

Reducing the prevalence of fossil fuels in all five of the country's energy mixes would reduce the GHGE in the agricultural and processing phases of the apple supply chain. Transitioning to an energy mix with a lower proportion of fossil fuels would support existing treaties as the Kyoto Protocol (United Nations, 2021a) and the Montreal Protocol (United Nations, 2021b) as well as supporting the United Nations

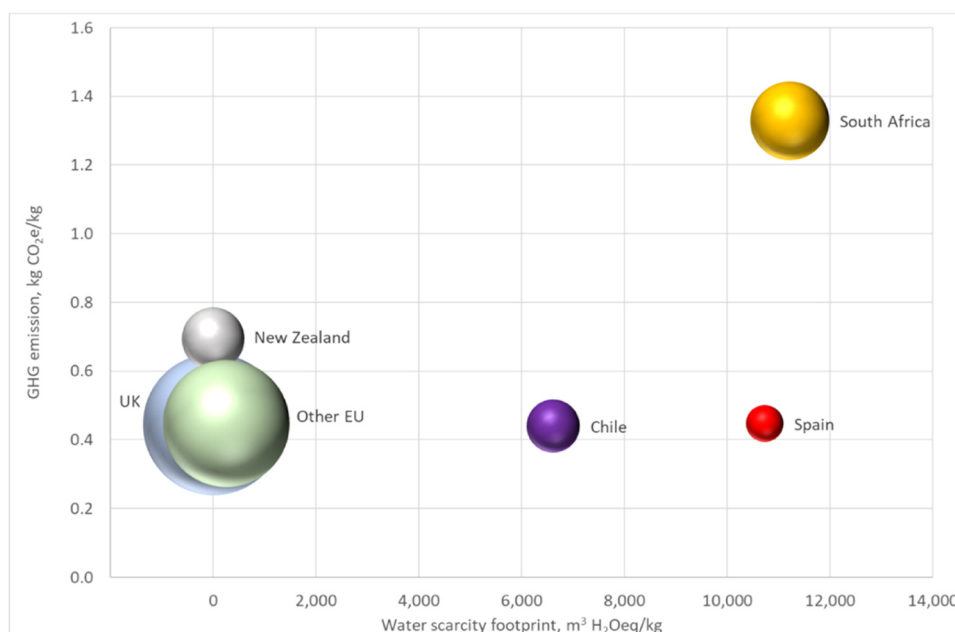


Fig. 3. Greenhouse gas emissions (GHGE), expressed as kg of carbon dioxide equivalents per kg of apples (kg CO₂e/kg), and water scarcity footprint, expressed as litres of water equivalents per kg of apples (L H₂Oeq/kg), sourced from different locations for the United Kingdom (UK) market (South Africa, Chile, Spain, New Zealand and Other European Union [EU]). Bubble size is proportional to the mass supplied.

Sustainable Development Goals numbers 7, 12 and 13 (United Nations, 2015). Improving the energy mix, particularly in the UK, would offer an opportunity to reduce the emissions associated with cold storage. The choice of CA technology can also impact the GHGE. Boschiero et al. (2019) found that the use of DCA storage was shown to have 36 % higher GHGE than ULO storage because of its higher electricity demand. 100-fold variation in GHGE emissions were given for cold storage (Longo et al., 2017; de Kock et al., 2019), demonstrating the need for standardisation in low-emission refrigeration. Lastly, there are developments in postharvest treatment that could help reduce the GHGE of the cold storage stage. The use of 1-MCP, as an alternative post-harvest storage method to CA, has been shown in several studies to delay apple fruit softening by inhibiting ethylene perception (Watkins, Nock and Whitaker, 2000; Watkins, 2008; Win et al., 2021). The use of 1-MCP could reduce GHGE of postharvest storage as it removes the requirement for facilities to regulate and monitor O₂/CO₂ levels, although its use in combination with DCA may enable storage at warmer temperatures to reduce GHGE from refrigeration (Köpcke, 2015). Although the use of 1-MCP is not approved for commercial use in all countries, it is approved in all five of the countries in the scope of this study (Watkins, 2008).

Potential GHGE reductions from improved energy or cold storage practices are an important area for future mitigation, but they were not quantified in this study because doing so robustly requires region- and technology-specific data that are outside the scope of our dataset. Credible scenario quantification would demand i) baseline refrigeration and postharvest energy use by exporting region and storage pathway (e. g. bulk cold storage, CA storage, refrigerated transport), ii) representative storage durations and throughput, and iii) accurate electricity grid carbon intensities and likely technology adoption rates for each origin. These inputs are highly variable across supplier countries and years; in their absence any numeric scenario would depend on extensive, location-specific assumptions and could therefore be misleading. We herein provide a qualitative assessment: energy and cold-chain improvements (more efficient refrigeration equipment, reduced losses, and lower carbon electricity) would be expected to lower per-kg GHGE from post-harvest stages, but the magnitude of reduction will depend strongly on origin-specific practices and electricity decarbonisation.

4.2. Addressing blue water scarcity footprint

WSF estimates are highly polarised between areas of negligible WSF (Italy, New Zealand, Ireland) and substantial (Chile, Spain, South Africa), corresponding with past findings that the water footprint increases with imported produce compared to home-grown fruit (Frankowska et al., 2019). Per kg, the water footprint of apple is comparatively small when compared with other fruit types – it is only 3.9 % of avocado (Frankowska et al., 2019), but given the large market volume the resultant WSF impact of apple will be substantial in import sourcing countries.

Yield enhancement through irrigation will negatively impact sustainability (Rosa, 2022), but management practices which enhance water use efficiency may mitigate this. Irrigation demand may vary between agronomic need (e.g. overhead spraying for spring frost protection or to sustain growth during drought), and will have a significant impact on fruit quality and nutrient management practice (Musacchi and Serra, 2018). Firstly, increasing yields provides an opportunity to decrease the water scarcity footprint per 1 kg of apples retailed, as the impacts at farm level are shared across a larger quantity of produce. Although some additional water may be required to achieve higher yields, the benefit of increased yields typically outweighs the increase in water consumption, therefore closing the yield gap in South Africa, Chile and France would improve the water scarcity footprint per 1 kg of fresh apples. Management practices which enhance water use efficiency such as deficit irrigation or rootstock selection may reduce crop irrigation demand (Musacchi and Serra, 2018). Reduction of evapotranspiration

may also reduce irrigation demand, such as the use of protective netting. Although primarily used for protection against hail and sunburn damage, protective netting has a plethora of other impacts, including reduced water consumption (Mupambi et al., 2018; Szabó, Tamás and Nagy, 2021). Protective netting usage changes the microclimate around the orchard system, allowing less solar radiation to reach the trees and lower wind speeds, with the total potential evapotranspiration being reduced by approximately 30 % under netting (McCaskill et al., 2016). This results in lower water requirements in the orchard system. When experiencing periods of moderate water stress, López et al., (2018) found that trees under netting had yields 4–8 kg higher than those without nets, demonstrating that the use of nets during periods of moderate water stress can help maintain yields. Under severe water stress conditions however, the installation of netting was not effective. Overall, the installation of nets when moderate water stress is expected could be beneficial to both water consumption and maintaining yields, alongside other benefits such as hail and sunburn damage. This is of particular relevance to Chile and South Africa, where periods are moderate water stress can frequently occur and adaptations will be required for increased water stress in the future (Olabanji et al., 2020; Valdés-Pineda et al., 2014). Lastly, water scarcity footprints could be decreased through large infrastructural changes. For example, the Berg-Breede Basin, the key water source in the Western Cape region of South Africa, is projected to have a water deficit of 834 million m³ /year due to trebled urban and domestic demand as well as increased industrial use. Some organisations hypothesise that agriculture will be required to transfer some of its water resource allocation to other users, and this expectation has resulted in the pursuit of investment in an irrigation system using the Olifants/Doring River system as an alternative (Vink and Tregurtha, 2005). If these infrastructural changes were to incorporate methods to improve the seasonality of water withdrawal, for example the use of a dam which is filled during times of water abundance which can then be drawn upon for irrigation during the seasons when water is scarce, the overall water scarcity index for the region would be reduced, and therefore the resulting water scarcity footprint.

Reducing GHGE and WSF in apple supply chains can involve trade-offs. For example, energy intensive storage technologies like CA or DCA can extend shelf life and reduce food loss, lowering GHGE per kg of fruit delivered, but they increase electricity demand, which may raise emissions in regions reliant on fossil fuels. Conversely, irrigation and protective measures such as netting can reduce WSF by increasing yields or lowering evapotranspiration, yet irrigation powered by fossil-fuel pumps can increase GHGE. These examples highlight that interventions to mitigate one environmental impact may inadvertently exacerbate another, emphasising the need for integrated strategies that balance carbon and water impacts across production, storage, and transport.

4.3. Sourcing strategies

Alongside actions that reduce the blue water scarcity footprint and GHGE within the supply chain, the UK's choice of sourcing strategy can also reduce these environmental impacts. At national level, UK fresh apple supply is reliant on domestic production and imports from six key trading partners. Although Germany and Italy have not been evaluated in this study, if the water scarcity footprint and GHGE values for France are used as proxy, and all imports from Europe are combined, we can consider the impacts at a national level. Although South Africa represents less than 15 % of supply, it accounts for over 70 % of the blue water scarcity impacts of UK fresh apple supply. Similarly, Chilean produce accounts for a higher proportion of blue water scarcity than its proportion of supply, by a factor of approximately three. The northern hemisphere countries supply over 70 % of UK apple demand, however they only account for 8 % of the blue water scarcity footprint and 57 % of the GHGE of the UK consumption. Consequently, adjusting the mix of countries from which the UK sources fresh apples is an approach which

can be used to reduce the environmental impacts at a national level (Fig. 4).

The impacts of alternative sourcing strategies can be estimated. For example, South Africa is the southern hemisphere country from which the UK imports the largest quantity of apples. If produce currently sourced from South Africa was to be sourced from Chile instead, the total blue water scarcity footprint for UK supply would decrease by 30 %, and the GHGE would decrease by 13 %. However, sourcing from a single or narrow range of countries can result in increased exposure to risk and vulnerability to shocks in the food system (Kummu et al., 2020). Typical calculations of a country's GHGE use a production approach, rather than evaluating the emissions of a country's consumption, which can result in the "off-shoring" of a country's environmental impacts (Motaal, 2011). When apple supply is assessed using UK domestic production only, the environmental impacts are severely underestimated because imports are excluded. Compared with the footprint of all apples consumed in the UK (domestic + imported), the calculated impacts are 99.6 % lower for blue water scarcity footprint and 63.8 % lower for greenhouse gas emissions.

4.4. Apple beverages: important product to consider

Although this study focuses on fresh apples, apple beverages represent a major component of global apple use and therefore contribute to the overall environmental footprint of the sector. Approximately 21.5 % of global apple production is processed into beverages such as juice and cider, with juice being the dominant processed product (Ampese et al., 2023). Juice production involves milling and pressing apples, generating pomace as a by-product, and the energy required for these stages is a principal contributor to GHGE (Lyu et al., 2020).

Processing can significantly increase emissions relative to fresh fruit. For dried apple, 73 % of total GHGE (4.72 kg CO₂e/kg) results from the energy demands of processing, although impacts can be reduced through multi-stage freeze-drying rather than conventional heated drying (De Marco et al., 2015). Processing emissions for juice are lower per kilogram of product (0.17 kg CO₂e/kg for fresh and 0.44 kg CO₂e/kg for concentrate), but overall impacts rise when considering packaging and cold chain requirements, contributing a further 1.3 kg CO₂e/kg (Frankowska et al., 2019).

In the UK, juicing represents a minority route due to comparatively low value, yet around one third of the domestic apple production is used for cider (DEFRA, 2020), making this the predominant processing pathway for UK grown apples. Cider production incurs additional impacts from fermentation and bottling in glass, resulting in GHGE around 50 % higher than juice alone (Smith and Lal, 2022). Importing processed products can further elevate impacts due to transport, with juice from concentrate generating 1.71 kg CO₂e/kg between production and retail

compared with 1.26 kg CO₂e/kg for UK produced juice (Frankowska et al., 2019).

While processing increases environmental burdens, it can also reduce losses by utilising lower grade fruit and extending shelf life. Pomace (25–30 % of original fruit mass), may also be valorised through animal feed or other uses, creating opportunities to offset impacts within the supply chain (Lyu et al., 2020).

Even though the paper does not focus on beverages, literature review highlighted that besides fresh apple, significant GHGE result from processing, which is dominated by beverage production such as juice and cider, or dehydrated apple for reconstitution in food such as infant feed (Soler et al., 2009; Soto-Silva et al., 2017). Additional energy needs during processing can significantly increase GHGE, with 73 % of GHGE for UK dried apple (4.72 kg CO₂e/kg) incurred during processing (Frankowska et al., 2019). Impacts from drying can be reduced by using multi-stage freeze drying rather than conventional heated drying, although costs can be prohibitive (De Marco et al., 2015). Juicing generates smaller GHGE impacts during processing, contributing 0.17 kg CO₂e/kg for fresh and 0.44 kg CO₂e/kg for concentrated juice products, although more significant contributions will be made through requirements for packaging (0.6 kg CO₂e/kg) and refrigeration during transport and retail (0.7 kg CO₂e/kg) that is not required for dried products (Frankowska et al., 2017). Juicing of UK apples is a minority route due to low market value, but one third of UK apple production is used for cider (DEFRA, 2020) making this the predominant processing route for UK grown apples. Cider production from juice will incur additional impacts through fermentation and bottling in glass, with GHGE 50 % greater than that of juice alone (Smith and Lal, 2022). Processing impacts vary significantly between country of production, with imported juice from concentrate incurring GHGE of 1.71 kg CO₂e/kg between production and retail compared with 1.26 kg CO₂e/kg for UK juice (Frankowska et al., 2019) due to differences during production and transport. While UK production for juice and dehydrated apple is minimal due to low market value, c. 33 % of UK apple production is used for cider (DEFRA, 2020). Cider production will incur significant GHGE due to additional processing (fermentation) and packaging (glass bottles) requirements, giving GHGE of 3.7 kg CO₂e/kg, or 150 % that of juice. The reliance on imported dried apple and apple juice will increase GHGE due to transport, and while emissions from processing are unlikely to vary between country of origin significant variation in estimates for the impact of processing may hinder analysis of the effect of processing supply (Frankowska et al., 2019; de Kock et al., 2019).

While processing increases the environmental impacts of apple production, this may be partially offset by reducing the impact of apple loss/waste through utilisation of lower quality fruit and shelf life extension. While processing may also generate additional waste streams (e.g. pomace from juicing, constituting 25–30 % of the original fruit's weight) this may have alternative uses within the supply chain to further reduce environmental impacts (Lyu et al., 2020).

4.5. Limitations in the methodology

A wide range of methods and assumptions were used but most studies followed life cycle assessment procedures following ISO 14044 and 14040 (2006). A few used other approaches or did not explicitly state the method. The literature review resulted in studies employing range of methods, including PAS 2050 (British Standards Institution, 2008), Greenhouse Gas Protocol (Greenhouse Gas Protocol, 2021) and LCAs using a range of ecoinvent databases and ISO standards (Ecoinvent, 2021; ISO, 2016). These studies each had different scopes, system boundaries and inventories, hindering direct comparisons between separate studies (Clune et al., 2017). However, despite the difficulties in making direct comparisons, a systematic literature review remains a valid approach when evaluating the current state of research and when aiming to evaluate a range of values. The use of a systematic

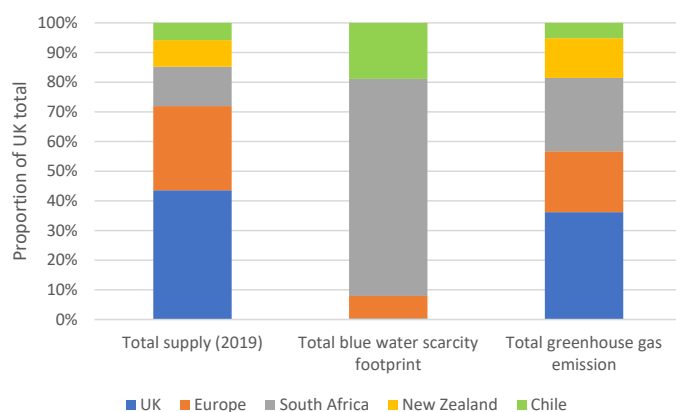


Fig. 4. Proportion of supply, blue water scarcity footprint and greenhouse gas emissions for UK apple fresh apples, for produce with country of origin in the United Kingdom (UK), Europe, South Africa, New Zealand and Chile.

review approach has allowed us to draw initial findings when comparing countries, as well as highlighting the limited amount of research for Chile and South Africa, with only one paper each, written in 2021 and 2019 respectively.

Within the agricultural stage, the GHGE of orchard systems can be evaluated using a variety of approaches, with inconsistencies as to the inclusion of the nursery phase, carbon sequestration and the number of harvest seasons (Table S4). Alaphilippe (2016) found that when unproductive phases were included, they represented 15 % of the GHGE of an orchard system, therefore the impact to the results of including different stages is sizeable. These inconsistencies could be overcome through the use of a universally agreed standard in orchard systems, for example PAS 2050, described as “milestone in carbon footprinting in horticulture” (Blanke, 2014).

The maritime shipping stage can also be evaluated using a variety of methods, sometimes resulting in contradictory values. The seven values obtained for the GHGE of shipping from New Zealand to the UK are wide ranging, with the maximum value over seven times larger than the minimum value, resulting in a high level of uncertainty when drawing conclusions for the total GHGE for New Zealand produce. Firstly, this is driven by the overall approach used and the associated scope, for example Fitzgerald (2011) obtain values using a desktop exercise of key emissions, whereas McLaren et al. (2009) use a full LCA methodology and include smaller emissions contributors in their calculations, such as the backhaul of empty shipping containers. Secondly, the shipping emissions differ due to factors such as the assumed distance travelled, with Saunders and Barber (2017) assuming a direct path to the UK of 17,840 km, whilst Fitzgerald et al. (2011) assume a mean annual value of 23,800 km, allowing for other ports to be visited during transit. The latter approach is likely to be more accurate given that only 13 % of apples exported from New Zealand are shipped directly to their final destination (Fitzgerald et al., 2011). A number of other inconsistent assumptions also arise, for example the emissions from fuel used (2.68 kgCO₂/L diesel assumed in Saunders and Barber 2017 compared to 3.55 kgCO₂/L heavy fuel oil assumed in Rizet et al., 2012). Overall, given the size of the contribution to total GHGE (47–70 % of the New Zealand total value) a universally agreed method would be beneficial not only for reducing the uncertainties within findings of this study, but for the estimated 31 % of the world's food supply chain which requires refrigerated transport (Jolly et al., 2000).

The method adopted in this study resulted in few GHG values for the road transportation stage. This is due to the nature of the search terms, where inclusion of the terms “apple” or “*Malus domestica*” were compulsory, and therefore papers about generic road transportation were excluded from the review. However, given the small overall contribution of road transportation to the GHGE of the total apple supply chain, the uncertainty around these values is of less concern for the purposes of this study.

Postharvest treatment in particular shows significant variation between studies, such as storage temperatures, longevity and handling practice (e.g. CA/DCA, chemical use) or inclusion of refrigerant type and leakage on GHGE calculations. When considering the contribution of cold storage to the GHGE, it should be noted that the values obtained in the literature review assumed 5–7 months in storage (Frankowska, Jeswani and Azapagic, 2019; Saunders and Barber, 2017; Webb et al., 2013). We can estimate the impact of 10 months storage by extrapolating the mean monthly value from the three studies, resulting in 0.25 kgCO₂e/kg for the storage stage. This value is comparable to the mean maritime shipping stages of South Africa of 0.26 and 0.24 kgCO₂e/kg respectively. However, greater understanding of the environmental impacts of postharvest handling strategies will be necessary to ensure accurate comparisons between alternative supply chains.

A limitation of this approach is the lack of accounting for waste, as storing apples for greater than four months results in gradually higher levels of loss, reaching an estimated 15–40 % after 10 months (Milà I Canals et al., 2007). This quantity of wastage would impact both the

GHGE and blue water scarcity footprint per 1 kg of apples at RDC, as a higher quantity of harvested apples would be required to result in 1 kg viable for retail. Milà I Canals et al. (2007) give a thorough evaluation of four different apple sourcing scenarios across different times of the year (October, January, April, August), accounting for waste levels, and evaluates the primary energy usage for each scenario. The approach of evaluating four different times of year is beneficial as it is effective in demonstrating how sourcing impacts differ during the annual cycle, rather than considering only one point in time as is typical in the broader literature, including the papers within this systematic review. A similar study for GHGE would be a valuable next step.

The stages of transportation from farm to port, and the stage of port operations, were rarely included in studies, and when they were included they were found to be a minor contributor to the total supply chain (for example Chilean port operations emitted 1.2 % of total GHGs evaluated in the study by Iriarte et al. 2021).

Overall, comparing studies of GHGE is difficult due to different methodologies used. A consistent approach applied across all five countries would be more conclusive and draw fair comparisons. The development of a consensus for a universal method would be of particular interest and importance to those retailers who wish to publish carbon footprints on product packaging (Rondoni and Grasso, 2021).

In practice there is a wide range of environmental externalities of apple supply chains which would add further trade-offs to those considered above. For example, LCA studies typically consider the impact categories of climate change, photochemical oxidants formation, acidification, nutrification, human toxicity and ecological toxicity (Milà I Canals, Burnip and Cowell, 2006). In addition, apple supply chains have both social and economic externalities. Growing high-value horticulture crops generates substantive socio-economic benefits in low income countries. It can enhance the welfare of small-scale farming communities (Maertens and Swinnen, 2012), provide secure employment, lead to higher, and more stable, incomes (Maertens and Swinnen, 2012) for large numbers of people and empower women in rural communities (Krumbiegel et al., 2020). Economic and social externalities of fruit and vegetable supply chains are of critical importance and requires further research. However, some recent developments have been made in this area. For example Gao et al. (2021) propose a conceptual framework for the consideration of environmental and economic trade-offs of orchards in Chinese drylands).

5. Conclusions

The environmental impacts of UK apple supply vary widely by country of origin, with southern hemisphere imports, particularly from South Africa and Chile, contributing high BWS due to irrigation demands, while northern hemisphere imports generally have lower water impacts but moderate GHGE from storage and energy use. Cold storage is a key driver of GHGE, and strategies to reduce water use, such as irrigation efficiency or protective netting, can sometimes increase emissions, highlighting trade-offs between carbon and water impacts. Processing and transport add additional emissions but can reduce losses and valorise by-products, further demonstrating the need for integrated supply chain strategies. Mitigation opportunities exist at multiple stages, including improved yields, storage efficiency, sourcing strategies, and infrastructure to manage water availability. Adjusting the mix of sourcing countries can also reduce impacts, though over-reliance on a narrow set of origins may increase supply chain vulnerability. This study has highlighted limitations in data available, including inconsistent life cycle assessment methods, incomplete data for some countries, and partial accounting for postharvest losses and processing impacts. Future work should generate region- and technology-specific data, quantify trade-offs between GHGE and water use, and incorporate social and economic factors to support more sustainable supply chains.

Overall, considering multiple environmental indicators provides a clearer understanding of apple supply chain impacts, enabling

policymakers, retailers, and consumers to make more informed decisions to promote a resilient and sustainable apple supply for the UK.

CRedit authorship contribution statement

Tim Hess: Supervision, Resources, Formal analysis, Data curation, Conceptualization. **Hannah Martin:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Ewan Gage:** Writing – review & editing, Formal analysis. **Natalia Falagan:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization.

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. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.agwat.2025.110070](https://doi.org/10.1016/j.agwat.2025.110070).

Data availability

Data will be made available on request.

References

- Aldaya, M.M., Allan, J.A., Hoekstra, A.Y., 2010. Strategic importance of green water in international crop trade. *Ecol. Econ.* 69 (4), 887–894. <https://doi.org/10.1016/j.ecolecon.2009.11.001>.
- Ampese, L.C., Ziero, H.D.D., Velásquez, J., Sganzerla, W.G., Martins, G., Forster-Carneiro, T., 2023. Apple pomace management by anaerobic digestion and composting: a life cycle assessment. *Biofuels Bioprod. Bioref.* 17, 29–45. <https://doi.org/10.1002/bbb.2446>.
- Audley, E., Brander, M., Chatterton, J., Murphy-Bokern, Williams, A. (2010). How low can we go? An assessment of greenhouse gas emissions from the UK food system and the scope to reduce them by 2050. Food Climate Research Network, WWF UK.
- Blanke, M.M., 2014. Possible implications of the new PAS 2050-1 hort carbon footprint standard (March 2012) for orchard management. *Acta Hortic.* (1058), 137–144. <https://doi.org/10.17660/ActaHortic.2014.1058.14>.
- Boschiero, M., Casera, C., Kelderer, M., 2018. Carbon footprint of innovative plastic covers used as insect and pest control system in organic apple orchards. *EcoFruit. Proc. 18th Int. Conf. Org. Fruit. Grow.* 71–77.
- Boschiero, M., Zanotelli, D., Ciarpica, F.E., Fadanelli, L., Tagliavini, M., 2019. Greenhouse gas emissions and energy consumption during the post-harvest life of apples as affected by storage type, packaging and transport. *J. Clean. Prod.* 220, 45–56. <https://doi.org/10.1016/j.jclepro.2019.01.300>.
- Boulay, A.M., Lenoir, L., 2020. Sub-national regionalisation of the AWARE indicator for water scarcity footprint calculations. *Ecol. Indic.* 111. <https://doi.org/10.1016/j.ecolind.2019.106017>.
- British Standards Institution. (2008). Guide to PAS 2050. Available at: https://aggi.e-horticulture.tamu.edu/faculty/hall/publications/PAS2050_Guide.pdf (Accessed: June 22, 2021).
- Clune, S., Crossin, E., Verghese, K., 2017. Systematic review of greenhouse gas emissions for different fresh food categories. *J. Clean. Prod.* 140, 766–783. <https://doi.org/10.1016/j.jclepro.2016.04.082>.
- de Kock, L., Russo, V., von Blottnitz, H., 2019. Carbon intensive but decarbonising quickly? Retrospective and prospective life cycle assessments of South African pome fruit. *J. Clean. Prod.* 212, 139–150. <https://doi.org/10.1016/j.jclepro.2018.12.026>.
- De Marco, I., Miranda, S., Riemma, S., Iannone, R., 2015. Environmental assessment of drying methods for the production of apple powders. *Int. J. Life Cycle Assess.* 20, 1659–1672. <https://doi.org/10.1007/s11367-015-0971-y>.
- DEFRA. (2020). Latest horticulture statistics - GOV.UK. Available at: <https://www.gov.uk/government/statistics/latest-horticulture-statistics> (Accessed: July 6, 2021).
- DEFRA. (2021). United Kingdom Food Security Report 2021: Theme 2: UK Food Supply Sources. Available at: <https://www.gov.uk/government/statistics/united-kingdom-food-security-report-2021-theme-2-uk-food-supply-sources#united-kingdom-food-security-report-2021-theme-2-indicator-2-1-1> (Accessed: September 7, 2023).
- Ecoinvent. (2021). ecoinvent. Available at: <https://www.ecoinvent.org/> (Accessed: July 27, 2021).
- Fitzgerald, W.B., Howitt, O.J.A., Smith, I.J., Hume, A., 2011. Energy use of integral refrigerated containers in maritime transportation. *Energy Policy* 39 (4), 1885–1896. <https://doi.org/10.1016/j.enpol.2010.12.015>.
- Frankowska, A., Jeswani, H.K., Azapagic, A., 2019. Life cycle environmental impacts of fruits consumption in the UK. *J. Environ. Manag.* 248. <https://doi.org/10.1016/j.jenvman.2019.06.012>.
- Gao, X., Zhao, X., Wu, P., Yang, M., Ye, M., Tian, L., Zou, Y., Wu, Y., Zhang, F., Siddique, K.H.M., 2021. The economic–environmental trade-off of growing apple trees in the drylands of China: a conceptual framework for sustainable intensification. *J. Clean. Prod.* 296. <https://doi.org/10.1016/j.jclepro.2021.126497>.
- Greenhouse Gas Protocol. (2021). Greenhouse Gas Protocol. Available at: <https://ghgprotocol.org/> (Accessed: June 22, 2021).
- Hess, T., Andersson, U., Mena, C., Williams, A., 2015. The impact of healthier dietary scenarios on the global blue water scarcity footprint of food consumption in the UK. *Food Policy* 50, 1–10. <https://doi.org/10.1016/j.foodpol.2014.10.013>.
- Hess, T., Sutcliffe, C., 2018. The exposure of a fresh fruit and vegetable supply chain to global water-related risks. *Water International* 43 (6), 746–761. <https://doi.org/10.1080/02508060.2018.1515569>.
- HM Revenue and Customs. (2022). UK Trade Info [Database]. UK Government. Available at: <https://www.uktradeinfo.com> (Accessed: June 30, 2023).
- Iriarte, A., Yáñez, P., Villalobos, P., Huenchuleo, C., Rebolledo-Leiva, R., 2021. Carbon footprint of southern hemisphere fruit exported to Europe: the case of Chilean apple to the UK. *J. Clean. Prod.* 293 (6), 126118. <https://doi.org/10.1016/j.jclepro.2021.126118>.
- ISO. (2014). Environmental Management – Water Footprint – Principles, Requirements and Guidelines. ISO 14046 Geneva, Switzerland. Available at: <https://www.iso.org/standard/43263.html> (Accessed: June 29, 2021).
- ISO. (2016). ISO 14040:2006 - Environmental management - Life cycle assessment - Principles and framework. Available at: <https://www.iso.org/standard/37456.html> (Accessed: July 27, 2021).
- Jolly, P.G., Tso, C.P., Wong, Y.W., Ng, S.M., 2000. Simulation and measurement on the full-load performance of a refrigeration system in a shipping container. *Int. J. Refrig.* 23 (2), 112–126. [https://doi.org/10.1016/S0140-7007\(99\)00044-4](https://doi.org/10.1016/S0140-7007(99)00044-4).
- Köpcke, D., 2015. 1-Methylcyclopropene (1-MCP) and dynamic controlled atmosphere (DCA) applications under elevated storage temperatures: Effects on fruit quality of ‘Elstar’, ‘Jonagold’ and ‘Gloster’ apple (*Malus domestica* Borkh). *Eur. J. Hortic. Sci.* 80 (1), 25–32. <https://doi.org/10.17660/eJHS.2015/80.1.4>.
- Krumbiegel, K., Maertens, M., Wollni, M., 2020. Can employment empower women? Female workers in the pineapple sector in Ghana. *J. Rural Stud.* 80, 76–90. <https://doi.org/10.1016/j.jrurstud.2020.05.012>. ISSN 0743-0167.
- Kummu, M., Kinnunen, P., Lehtikoinen, E., Porkka, M., Queiroz, C., Rööös, E., Troell, M., Weil, C., 2020. Interplay of trade and food system resilience: gains on supply diversity over time at the cost of trade interdependency. *Glob. Food Secur.* 24, 100360. <https://doi.org/10.1016/J.GFS.2020.100360>.
- Li, M., Jia, N., Lenzen, M., Malik, A., Wei, L., Jin, Y., Raubenheimer, D., 2022. Global food-miles account for nearly 20% of total food-systems emissions. *Nat. Food* 3 (6), 445–453. <https://doi.org/10.1038/s43016-022-00531-w>.
- Longo, S., Mistretta, M., Guarino, F., Cellura, M., 2017. Life Cycle Assessment of organic and conventional apple supply chains in the North of Italy. *J. Clean. Prod.* 140, 654–663. <https://doi.org/10.1016/j.jclepro.2016.02.049>.
- López, G., Boini, A., Manfrini, L., Torres-Ruiz, J.M., Pierpaoli, E., Zibordi, M., Losciale, P., Morandi, B., Corelli-Grappadelli, L., 2018. Effect of shading and water stress on light interception, physiology and yield of apple trees. *Agric. Water Manag.* 210, 140–148. <https://doi.org/10.1016/J.AGWAT.2018.08.015>.
- Lyu, F., Luiz, S.F., Azeredo, D.R.P., Cruz, A.G., Ajlouni, S., Ranadheera, C.S., 2020. Apple pomace as a functional and healthy ingredient in food products: a review. *Processes* 8, 319. <https://doi.org/10.3390/pr8030319>.
- Maertens, M., Swinnen, J.F.M., 2012. Gender and Modern Supply Chains in Developing Countries. *J. Dev. Stud.* 48 (10), 1412–1430. <https://doi.org/10.1080/00220388.2012.663902>.
- Mason, R., Simons, D., Peckham, C. and Wakeman, T. (2002). Life Cycle Modelling CO2 Emission for Lettuce, Apples and Cherries. DfT commissioned Transport 2000 study, part of Transport 2000's Wise Moves project.
- Mason-D'Croz, D., Bogard, J.R., Sulser, T.B., Cenacchi, N., Dunston, S., Herrero, M., and Wiebe, K., 2019. Gaps between fruit and vegetable production, demand, and recommended consumption at global and national levels: an integrated modelling study. *Lancet Planet. Health* 3 (7), e318–e329. [https://doi.org/10.1016/s2542-5196\(19\)30095-6](https://doi.org/10.1016/s2542-5196(19)30095-6).
- McCaskill, M.R., McClymont, L., Goodwin, I., Green, S., Partington, D.L., 2016. How hail netting reduces apple fruit surface temperature: a microclimate and modelling study. *Agric. For. Meteorol.* 226–227, 148–160. <https://doi.org/10.1016/J.AGRFORMET.2016.05.017>.
- Mekonnen, M.M., Hoekstra, A.Y., 2011. The green, blue and grey water footprint of crops and derived crop products. *Hydrol. Earth Syst. Sci.* 15, 1577–1600. <https://doi.org/10.5194/hess-15-1577-2011>.
- Milà I Canals, L., Burnip, G.M., Cowell, S.J., 2006. Evaluation of the environmental impacts of apple production using Life Cycle Assessment (LCA): case study in New Zealand. *Agric. Ecosyst. Environ.* 114 (2–4), 226–238. <https://doi.org/10.1016/j.agee.2005.10.023>.
- Milà I Canals, L., Cowell, S.J., Sim, S., Basson, L., 2007. Comparing domestic versus imported apples: a focus on energy use. *Environ. Sci. Pollut. Res.* 14 (5), 338–344. <https://doi.org/10.1065/espr2007.04.412>.
- Motaal, D., 2011. Emissions offshoring: repercussions for international trade. *Carbon Clim. Law Rev.* 5 (4), 466–476. Available at: <http://www.jstor.org/stable/24324071>.
- Mupambi, G., Anthony, B.M., Layne, D.R., Musacchi, S., Serra, S., Schmidt, T., Kalcsits, L. A., 2018. The influence of protective netting on tree physiology and fruit quality of apple: A review. *Sci. Hortic.* 236, 60–72. <https://doi.org/10.1016/j.scienta.2018.03.014>.

- Musacchi, S., Serra, S., 2018. Apple fruit quality: overview on pre-harvest factors. *Sci. Hortic.* 234, 409–430. <https://doi.org/10.1016/j.scienta.2017.12.057>.
- Olabanji, M.F., Ndarana, T., Davis, N., Archer, E., 2020. Climate change impact on water availability in the olifants catchment (South Africa) with potential adaptation strategies. *Phys. Chem. Earth Parts A/B/C.* 120, 102939. <https://doi.org/10.1016/j.pce.2020.102939>.
- Ray, A., De, S., 2020. Renewable electricity generation – Effect on GHG emission. *Encycl. Renew. Sustain. Mater.* 3, 728–735. <https://doi.org/10.1016/B978-0-12-803581-8.11015-X>.
- Ridoutt, B.G., Pfister, S., 2010. A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity. *Glob. Environ. Change* 20 (1), 113–120. <https://doi.org/10.1016/j.gloenvcha.2009.08.003>. ISSN 0959-3780.
- Rizet, C., Browne, M., Cornelis, E., Leonardi, J., 2012. Assessing carbon footprint and energy efficiency in competing supply chains: review – case studies and benchmarking. *Transp. Res. Part D Transp. Environ.* 17 (4), 293–300. <https://doi.org/10.1016/J.TRD.2012.01.002>.
- Rondoni, A., Grasso, S., 2021. Consumers behaviour towards carbon footprint labels on food: a review of the literature and discussion of industry implications. *J. Clean. Prod.* 301, 127031. <https://doi.org/10.1016/j.jclepro.2021.127031>.
- Rosa, L., 2022. Adapting agriculture to climate change via sustainable irrigation: biophysical potentials and feedbacks. *Environ. Res. Lett.* 17, 063008. <https://doi.org/10.1088/1748-9326/ac7408>.
- Saunders, C., Barber, A., 2017. Carbon footprints, life cycle analysis, food miles: global trade trends and market issues. *Political Sci.* 60 (1), 73–88. <https://doi.org/10.1177/003231870806000107>.
- Scheelbeek, P.F., Moss, C., Kastner, T., Alae-Carew, C., Jarmul, S., Green, R., Taylor, A., Haines, A., Dangour, A.D., 2020. United Kingdom's fruit and vegetable supply is increasingly dependent on imports from climate-vulnerable producing countries. *Nat. Food* 1 (11), 705–712. <https://doi.org/10.1038/s43016-020-00179-4>.
- Smith, M., Lal, P., 2022. Environmental and economic assessment of hard apple cider using an integrated LCA-LCC approach. *Sustain. Prod. Consum.* 32, 282–295. <https://doi.org/10.1016/j.spc.2022.04.026>.
- Soler, C., Soriano, J.M., Mañes, J., 2009. Apple-products phytochemicals and processing: a review. *Nat. Prod. Commun.* 4 (5), 659–670. <https://doi.org/10.1177/1934578X0900400504>.
- Soto-Silva, W.E., González-Araya, M.C., Oliva-Fernández, M.A., Plá-Aragónés, L.M., 2017. Optimizing fresh food logistics for processing: Application for a large Chilean apple supply chain. *Comput. Electron. Agric.* 136, 42–57. <https://doi.org/10.1016/j.compag.2017.02.020>.
- Stratton, A.E., Finley, J.W., Gustafson, D.I., Mitcham, E.J., Myers, S.S., Naylor, R.L., Otten, J.J., Palm, C.A., 2021. Mitigating sustainability tradeoffs as global fruit and vegetable systems expand to meet dietary recommendations. *Environ. Res. Lett.* 16 (5), 055010. <https://doi.org/10.1088/1748-9326/abe25a>.
- Szabó, A., Tamás, J., Nagy, A., 2021. The influence of hail net on the water balance and leaf pigment content of apple orchards. *Sci. Hortic.* 283, 110112. <https://doi.org/10.1016/J.SCIEN.2021.110112>.
- Trajer, J., Winiczenko, R., Drózd, B., 2021. Analysis of water consumption in fruit and vegetable processing plants with the use of artificial intelligence. *Appl. Sci.* 11 (21), 10167. <https://doi.org/10.3390/app112110167>.
- United Nations (2015) THE 17 GOALS | Sustainable Development. Available at: (<https://sdgs.un.org/goals>) (Accessed: August 8, 2021).
- United Nations (2021a) What is the Kyoto Protocol? | UNFCCC. Available at: (https://unfccc.int/kyoto_protocol) (Accessed: August 8, 2021).
- United Nations (2021b) About Montreal Protocol UNEP. Available at: (<https://www.unep.org/ozoneaction/who-we-are/about-montreal-protocol>) (Accessed: July 3, 2021).
- Valdés-Pineda, R., Pizarro, R., García-Chevesich, P., Valdés, J.B., Olivares, C., Vera, M., Balocchi, F., Pérez, F., Vallejos, C., Fuentes, R., Abarza, A., Helwig, B., 2014. Water governance in Chile: availability, management and climate change. *J. Hydrol.* 519, 2538–2567. <https://doi.org/10.1016/j.jhydrol.2014.04.016>.
- van Rijswijk, C., Salinas, G., Magana, D. (2025). World Fruit Map 2025. RaboResearch Food Agribusiness. Available at: (<https://www.rabobank.com/knowledge/q011486210-world-fruit-map-a-changing-basket-of-fruits-and-trade-flows>) (Accessed December 2, 2025).
- Vink, N., Tregurtha, N. (2005). Western Cape Agricultural Sector: Structure, performance and future prospects - an overview. Available at: (https://www.westerncape.gov.za/other/2005/10/agri_final_first_paper_overview.pdf) (Accessed: July 27, 2021).
- Watkins, C.B., 2008. Overview of 1-methylcyclopropene trials and uses for edible horticultural crops. *HortScience* 43 (1), 86–94. <https://doi.org/10.21273/HORTSCI.43.1.86>.
- Watkins, C.B., Nock, J.F., Whitaker, B.D., 2000. Responses of early, mid and late season apple cultivars to postharvest application of 1-methylcyclopropene (1-MCP) under air and controlled atmosphere storage conditions. *Postharvest Biol. Technol.* 19 (1), 17–32. [https://doi.org/10.1016/S0925-5214\(00\)00070-3](https://doi.org/10.1016/S0925-5214(00)00070-3).
- Webb, J., Williams, A.G., Hope, E., Evans, D., Moorhouse, E., 2013. Do foods imported into the UK have a greater environmental impact than the same foods produced within the UK? *Int. J. Life Cycle Assess.* 18 (7), 1325–1343. <https://doi.org/10.1007/S11367-013-0576-2>.
- Win, N.M., Yoo, J., Naing, A.H., Kwon, J.G., Kang, I.K., 2021. 1-Methylcyclopropene (1-MCP) treatment delays modification of cell wall pectin and fruit softening in 'Hwangok' and 'Picnic' apples during cold storage. *Postharvest Biol. Technol.* 180, 111599. <https://doi.org/10.1016/J.POSTHARVBIO.2021.111599>.
- World Health Organisation. (2012). Report of the Formal Meeting of Member States to conclude the work on the comprehensive global monitoring framework, including indicators, and a set of voluntary global targets for the prevention and control of noncommunicable diseases" 5–7 November. Available at: (https://apps.who.int/eb/NCDs/pdf/A_NCD_2-en.pdf).



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How green are my apples - The greenhouse gas emissions and blue water scarcity footprint of fresh apple supply chain

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