Global Food Security 40 (2024) 100734

Contents lists available at ScienceDirect

Global Food Security

journal homepage: www.elsevier.com/locate/gfs

# To what extent can agriculture be reshaped to address healthy and sustainable diets by boosting pulse production locally?

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## ABSTRACT

The consumption of unhealthy and environmentally unsustainable diets is a major societal challenge because of its impacts on human health and the environment. The adoption of micronutrient-rich diets with relatively low pressure on natural resources is an important development target at the intersection between sustainability and public health goals. Pulses are known for being rich in proteins and micronutrients, while having several environmental benefits. It is still unclear to what extent improving the nutritional content of diets by boosting pulse consumption can address health concerns associated with micronutrient deficiency without exacerbating environmental impacts. Here we evaluate to what extent environmentally sustainable, healthy diets can be achieved by increasing pulse production, while reducing the areas cultivated with cereals. To that end, taking as case studies two low/middle income countries (i.e., Pakistan and Nigeria) with high prevalence of nutritional diseases among children and women, we study different crop replacement scenarios that can boost pulse supply and comply with the micronutrient requirements suggested by the EAT-Lancet Commission. We find that in Nigeria the recommended pulse intake requirement can be met by increasing the domestic production of pulses, while saving 27% of water consumption. Conversely, in Pakistan the recommended levels of pulse intake are barely met because of the limited area suitable for pulse production. Overall, the current low yields of pulses and the limited availability of land suitable for pulse production are the main constraints to their supply in these two countries.

## 1. Introduction

Current diets link an environmentally unsustainable food system to human well-being or ill-being (Willett et al., 2019; GBD 2017 Diet Collaborators, 2019; Hoekstra and Wiedmann, 2014). Food production is happening at an unsustainable pace as a result of both agricultural expansion and intensified use of inputs such as water and fertilizer to enhance yields (Hoekstra and Wiedmann, 2014; Tilman et al., 2001; Tilman, 1999; Zabel et al., 2019). Global crop production is affected by land degradation and climate change-related stressors such as droughts and reduced rains (Fadnavis et al., 2019; Krishnan et al., 2016; Kumar et al., 2013; Sharma and Mujumdar, 2017; Zhang et al., 2017; Romanello et al., 2021; Vermeulen et al., 2012), which are expected to decrease yields worldwide (Khan et al., 2020). Socio-economic drivers such as increasing affluence in emerging economies will further increase the food demand, thus exacerbating future natural resource scarcity (Godfray et al., 2010), while about 800 million people worldwide remain undernourished, and billions suffer from diet-related diseases resulting from micronutrient deficiencies (Willett et al., 2019; GBD 2017 Diet Collaborators, 2019; Tulchinsky, 2010). The prevalence of both diet-related diseases and environmental degradation are expected to increase in the near future if food demand trends remain unchanged (Tilman and Clark, 2014).

The production of high-yielding cereals (e.g., rice, wheat, and maize), low in micronutrients content relative to pulses, has boomed in the last century, especially in developing countries (DeFries et al., 2015) as a result of food security policies pushing for increasing the availability of (and access to) staple crops such as grains. According to the Food and Agriculture Organization of the United Nations (FAO), cereals account for about half of the total caloric content of diets at the global scale (FAOSTAT, 2019a) thus allowing for diets that are often low in micronutrients, which explains why many parts of the world currently face environmental and health challenges as a result of nutritional deficiencies. For instance, South Asia's population suffers from diet related diseases (e.g., iron deficiency anemia) caused by the consumption of diets that are poor in micronutrients (Akhtar et al., 2013; Wieringa et al., 2019). At the same time, in some of these regions intensive production of staple crops such as cereals is associated with the overexploitation of natural resources, especially in India and Pakistan (Bhatt et al., 2016), including the depletion of freshwater resources (Rodell et al., 2009; Mukherjee, 2018).

A shift to more healthy and sustainable food consumption can help

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https://doi.org/10.1016/j.gfs.2023.100734
Received 13 February 2023; Received in revised form 27 July 2023; Accepted 26 November 2023

reduce environmental impacts and reduce the prevalence of nutritional diseases worldwide (Willett et al., 2019). Sustainable healthy diets should ensure both nutritional adequacy and sustainable use of natural resources within planetary boundaries (Willett et al., 2019; Rockström et al., 2009; Foley et al., 2011; Clark et al., 2019). Several studies (Willett et al., 2019; Springmann et al., 2018a, 2018b; Guo et al., 2022) have already highlighted the feasibility of shifting towards diets that improve the nutritional status of the global population, thereby averting diet-related diseases, while protecting natural resources. For instance, nutritional deficiencies can be sustainably addressed through an increase in the consumption of micronutrient-rich food (i.e., dietary diversification) (Nair et al., 2016). Davis et al. (2018) evaluated a scenario in which staple crops are replaced by other cereals, thus saving water while increasing micronutrient availability (e.g., zinc, iron) and allowing for improved diets. Recently, Food and Agriculture Organization of the United Nations (FAO) has been stressing the benefits of pulse consumption worldwide (Calles et al., 2019). Among all micronutrient-rich food, pulses are the most sustainable choice because of their several environmental and health benefits (FAO, 2016; Iriti and Varoni, 2017). Pulse consumption improves nutrient (e.g., iron, vitamin Bs, and zinc) intake (Mudryj et al., 2014; Thavarajah et al., 2009; Mitchell et al., 2021), while averting deaths (Springmann et al., 2018b; Guo et al., 2022).

Previous studies (Willett et al., 2019; Springmann et al., 2018b; Davis et al., 2016) have already linked the environmental impacts of dietary shifts and population wellbeing. Some studies have assessed the feasibility of shifts from cereals to food richer in micronutrients using domestic resources to ensure nutritional requirements. However, the extent to which such shifts can be implemented at no harm for the environment remains poorly understood. Thus, there is the need for high resolution studies investigating the feasibility of crop replacement strategies to achieve sustainable healthy diets.

Here we evaluate suitable crop replacement scenarios that could increase the nutritional content of diets. We consider replacing the production of staple crops that are currently overrepresented in diets relative to nutritional requirements with more nutritious and sustainable crops that are underproduced worldwide. Specifically, we consider increasing the supply of pulses by reducing the supply of cereals to amounts compatible with recommended healthy diets (Willett et al., 2019), while improving the efficiency of crop water and land use. Our study evaluates the compatibility of environmental and public health goals using physically based agro-hydrological modelling, thereby linking dietary recommendations to some countries' actual ability to sustainably produce nutritionally adequate food needed to control diet-related diseases. We then discuss the extent to which it is possible to effectively replace cereals with pulses by investigating farmers' ability to redirect production and consumers choices. Specifically, we consider low-to-middle income countries across Asia and Sub-Saharan Africa, namely, Pakistan and Nigeria, which are mostly self-sufficient in the production of staple food (i.e., cereals) (FAOSTAT, 2019a), show overrepresentation of cereals in diets with respect to nutritional requirements, and exhibit high prevalence of micronutrient deficiencies within their populations (Yue et al., 2022). These countries have recently enacted new food policies to boost the adoption of more sustainable and healthy diets (Government of Pakistan, 2018; Federal Republic of Nigeria, 2017a; Morgan and Fanzo, 2020; Federal Republic of Nigeria, 2017b). Here, Governments along with the World Food Programme (WFP) push to shift current food production locally to ensure the consumption of a more balanced diet (World Food Programme, 2018, 2019).

We develop crop replacement scenarios under the following conditions a) the extent of agricultural areas remains unchanged; b) the new pattern of crop distribution allows for a reduction in local water use compared to current crop production; c) replaced crops are either consumed at rates exceeding those recommended by healthy diets (e.g., cereals) or cash crops. To this end, we consider food production scenarios that allow people to follow the dietary requirements of the EAT-Lancet Commission (Willett et al., 2019). Specifically, we develop a pixel-scale crop replacement scheme that maximizes micronutrient availability while minimizing water use in irrigation based on spatially distributed agro-hydrological modeling. This framework accounts for the crop-specific planting and harvesting dates, crop rotations, as well as soil suitability for agricultural intensification with pulses in areas currently planted with cereals. We complement the biophysical analysis of crop replacement by evaluating the economic feasibility of the proposed crop shifts in the present food market conditions. We consider the profit generated by farmers by taking into account both production costs associated with agricultural inputs (i.e., fertilizers, pesticides, seeds, irrigation, machinery, labor and land rent) and revenues from agricultural production at the farm gate.

## 2. Methods

We evaluate the overall dietary imbalances existing in these two countries and then determine what would take to redress them by modifying diets and consequently changing the existing patterns of crop production. To meet micronutrient intake requirements, staple food that is domestically produced and consumed in excess with respect to the healthy diet requirements is replaced by pulses. Thus, we assess how the present diet differs from the requirements recommended by the EAT-Lancet Commission (Willett et al., 2019). Food consumption is evaluated using food varieties grouped according to Willett et al. (2019). We consider average data from 2014 to 2019 as the reference year and compute the current pulse and cereal supply net of waste and express it in grams per capita per day, using food supply data from the Food Balance Sheets (FBS) (FAOSTAT, 2019a) and applying food waste fractions from FAO (2011).

The reference sustainable diet from Willett et al. (2019) refers to a generic intake of 2500 kcal/cap/day and is not population specific. Therefore, to evaluate the reference healthy diet for each food group, $f$, specific for each Country, $c$, we scale the sustainable diet $D_f$ from Willett et al. (2019) to meet the caloric needs (i.e., average dietary energy requirement ($ADER_c$) (FAOSTAT, 2019b)) of the population of each Country, $c$, as follows:

$$HD_{c,f} = D_f \bullet \frac{ADER_c}{2500}$$

We then compute the difference between the current diet ($PD$) and the country-specific healthy diet ($HD$) for Nigeria and Pakistan. We evaluate crop replacement scenarios whereby overrepresented cereals in the diet (i.e., wheat (*Triticum aestivum*), maize (*Zea mays*), and rice (*Oryza sativa*)) are replaced with pulses to save water and increase overall nutrient intake. The FAO reports pulses as beans (*Phaseolus* and *Vigna*), chick-peas (*Cicer arietinum*), peas (*Pisum sativum*), cowpeas (*Vigna unguiculata*), lentils (*Lens culinaris*), pigeon peas (*Cajanus cajan*), broad beans (*Vicia faba*), lupins (*Lupinus*), bambara beans (*Vigna Subterranean*), and pulses not else specified (*Lablab purpureus*, *Psophocarpus tetragonolobus*, *Cyamopsis tetragonoloba*, *Mucuna pruriens* and *Sphenostylis stenocarpa*) (FAO, 1994). We consider increasing country-specific pulse supply according to each country's preferences in their diet derived from the Food Supply of the FBS (FAOSTAT, 2019a) and from food production/import from FAOSTAT (FAO, 2022) when data from FBS were not available. Here, we found cowpeas as the main pulse consumed in Nigeria (99% of supply) and lentils, chickpeas, beans, and peas for Pakistan.

We consider three different scenarios of crop replacement at pixel scale: a) (A1) - pulses replaced in areas currently planted with cereals (i.e., wheat, maize, and rice), b) (A2) - pulses replaced in areas currently planted with rice in Nigeria or cash crops (i.e., cotton) in Pakistan, c) (A3) - pulses replaced avoiding monoculture. Scenarios A1 and A2 allow monoculture of pulses. Scenario A3 does not allow for the monoculture of pulses but has cereal and pulse areas equally partitioned in each pixel

(5 arcminutes resolution) used in the discrete spatially explicit representation of the cultivated land in each country.

To replace crops, we maintain the total extent of cultivated land (i.e., irrigated + rainfed croplands) constant (Yu et al., 2020) (i.e., without increasing agricultural land). In addition, we replace only the harvested land having high suitability for pulse production according to soil properties. We consider pH as a limiting factor to pulse production because acidic soils can have a limited suitability to pulse production since they contain toxic ions for these crops, thereby reducing pulse crop yields and constraining nitrogen fixation in the soil (Ghimire et al., 2017; Burns et al., 2020; Graham and Vance, 2003). Using a soil pH dataset from Hengl et al. (2017) we consider pH data from 0 to 2 m, and then we scale up the pH map to five arcminutes to be consistent with the maps of the harvested areas. Crop replacement with pulses is then considered only in areas with pH values suitable for pulse production (i.e., close to 6, or in the range 5.5–8.0) (Uchida and Hue, 2000).

Moreover, we consider a precondition for replacement that the sowing and harvesting dates (taken from Portmann et al. (2010)) of replaced (i.e., cereals) and replacing (i.e., pulses) crops are consistent.

In addition to the improvement of the diet under the conditions listed above, cereals replacement with pulses is considered only if it allows for a reduction in water use. To that end, we compute the crop water requirement (CWR, expressed in volume per unit area or millimeters)), and its blue water (BW) (i.e., irrigation) and green water (GW) (i.e., precipitation-fed soil moisture) components both for cereals and pulses using the WATNEEDS crop water model (Chiarelli et al., 2020). This crop water requirement analysis is carried out in all the areas suitable for replacement, based on soil data (Hoogeveen et al., 2015), crop data (Siebert and Döll, 2010), crop calendar dates (Portmann et al., 2010) and climate data from 2014 to 2019 from Funk et al. (2015). WATNEEDS (Chiarelli et al., 2020) couples a soil water balance at the daily time scale with a calculation of evapotranspiration using the Penman-Monteith method, adjusted with crop-specific coefficients. We describe WATNEEDS in detail in the supplementary materials. Thus, for irrigated harvested areas, crop replacement occurs in each cell when BW consumption of pulses is lower than the BW consumption of replaced crops (i.e., cereals). Because most pulse production is currently rainfed, the replacement of irrigated cereals with pulses is associated with the intensification of pulse farming.

We also define the water savings (i.e., BW and GW for irrigated areas and GW for rainfed areas) as the volume of water saved when shifting crops. We compute this quantity in percentage (%) of water saved compared to current crop allocation.

We also assess the grey water (gW) footprint of nitrogen applications in current cereal and pulse production following the methodology by Mekonnen and Hoekstra (2011). We use the same country-scale nitrogen application data in kg/ha used in the production cost analysis (see below). We assume that 10% of these nitrogen applications is leached into the water system and that the baseline concentration therein is zero. We then compute the grey water footprint ($m^3$/ton) by dividing the quantity of nitrogen leached from the soil by the maximum recommended concentration (10 mg/L of nitrate nitrogen (Mekonnen and Hoekstra, 2011)) and the yield. We also evaluate the total volume of grey water (GW) in millions of cubic meters for each scenario A1, A2, A3.

We acknowledge that we compute grey water only for nitrogen application, thus omitting the grey water from phosphorus and pesticide applications.

Specifically, the crop replacement scheme was implemented according to the following steps. First, we identify the harvested areas currently cultivated with cereals that are suitable for producing pulses according to soil pH values, GAEZ crop soil suitability maps (FAO and IIASA, 2022) and synchronicity of crop calendar between the replaced crop and pulses. Then, we consider replacing cereals with pulses in these areas to meet (either completely or partly) the pulse consumption needs of each country, while reducing cereal production. To this aim, we 1) shift rainfed and irrigated areas currently harvested with cereals to pulse production; 2) compute the increase in pulse production and the decrease in cereal production in tons by multiplying these harvested areas by the corresponding yields; 3) evaluate the total increase in pulse consumption (i.e., supply net of food losses and waste) and decrease in cereal consumption at Country scale in grams per capita per day. We run this procedure keeping the supply of cereals above the requirements of the recommended healthy diet (HD) values. In case this condition is not satisfied, we replace cereals with pulses starting from suitable areas with the highest water savings. We continue the replacement in areas with decreasing water savings until the above condition is met. Spatially distributed maps of crop replacement areas are reported in the Supplementary Materials for each Country (Fig. S1).

To compute the per capita cereal and pulse consumption in each scenario, we use spatially distributed yields from SPAM2010 (Spatial Production Allocation Model) (Yu et al., 2020), population data consistent with the current scenario, PD, from FBS (FAOSTAT, 2019a), and food loss and waste rates from FAO (2011). Moreover, regarding the yield of pulses, we consider the average of all available pulses' yields weighted on their harvested areas. Then, we interpolate yields on all the suitable areas. Lastly, we define the pulse 'gap' ($GAP_i$) as the difference between healthy diet requirement ($HD$) and pulse supply according to the replacement scenario $A_i$ ($D_{A_i}$):

$$GAP_{i,c} = \frac{HD_c - D_{A_i}}{HD_c} \quad (\text{with } GAP_i = 0 \text{ if } HD < D_{A_i})$$

Healthy diet requirement for pulses refers to the recommended values of the country-specific sustainable diet. We consider total fulfillment (hence, $GAP_i = 0$) in the case of pulse supply higher than or equal to healthy recommendations.

We evaluate how micronutrient availability changes with the proposed agricultural intensification scenarios. Here, we assume that food availability is a proxy of food intake. To assess the iron, caloric and protein content of diets (PD, A1, A2, A3, HD), we rely on data from FoodData Central (U.S. Department of Agriculture, 2019), using mean nutritional properties for the food consumed in these two Countries in the current scenario (PD) and in the replacement scenarios (A1, A2, A3). For each micronutrient we consider as reference intake the RNI (Reference Nutrient Intake) and EAR (Estimated Average Requirement) which ensure the wellbeing of the 97.5% and 50% of the population, respectively. These data were taken for key micronutrients from the Supplementary Materials from Damerau et al. (2020) and adjusted to the country-specific age structure of the population from United Nations (2019). First, we consider the micronutrient deficit between current diet (PD) and the RNI and EAR (if any) and call it micronutrient inadequacy, then we evaluate how crop replacement can reduce this deficit. To do so, we compute the ratio between the increase in micronutrient availability in each scenario A1, A2, A3 and the corresponding micronutrient inadequacy (if any). We show only the micronutrient for which there is dietary inadequacy and pulse replacement is able to increase their availability.

We also assess to what extent the crop replacements we are envisioning (i.e., the shift from cereal to pulse production) would be economically feasible, based on suitable crop yields and present food market conditions. To do so, we compare ex post profits, revenues, and costs in $/ha for both cereals and pulses in Nigeria and Pakistan. We use fixed producer prices from FAOSTAT (FAO, 2022) and fixed costs available from literature without accounting for the possible change in prices following replacement scenarios. Yet, replacing cereals with pulses could increase the price of cereals and decrease the price of pulses so potentially inducing farmers to return to current cropping system. We illustrate the methods for this economic analysis in the supplementary materials.

## 3. Results

Comparing the present diet (PD) consumed in each country to the country-specific sustainable diet, we find that cereals are overrepresented relative to nutritional requirements while pulses are underconsumed in the two countries analyzed (Fig. S2, Fig. 1a). Currently, daily caloric supply from cereals contributes to about 50% of the daily dietary calories, a quantity much higher than the

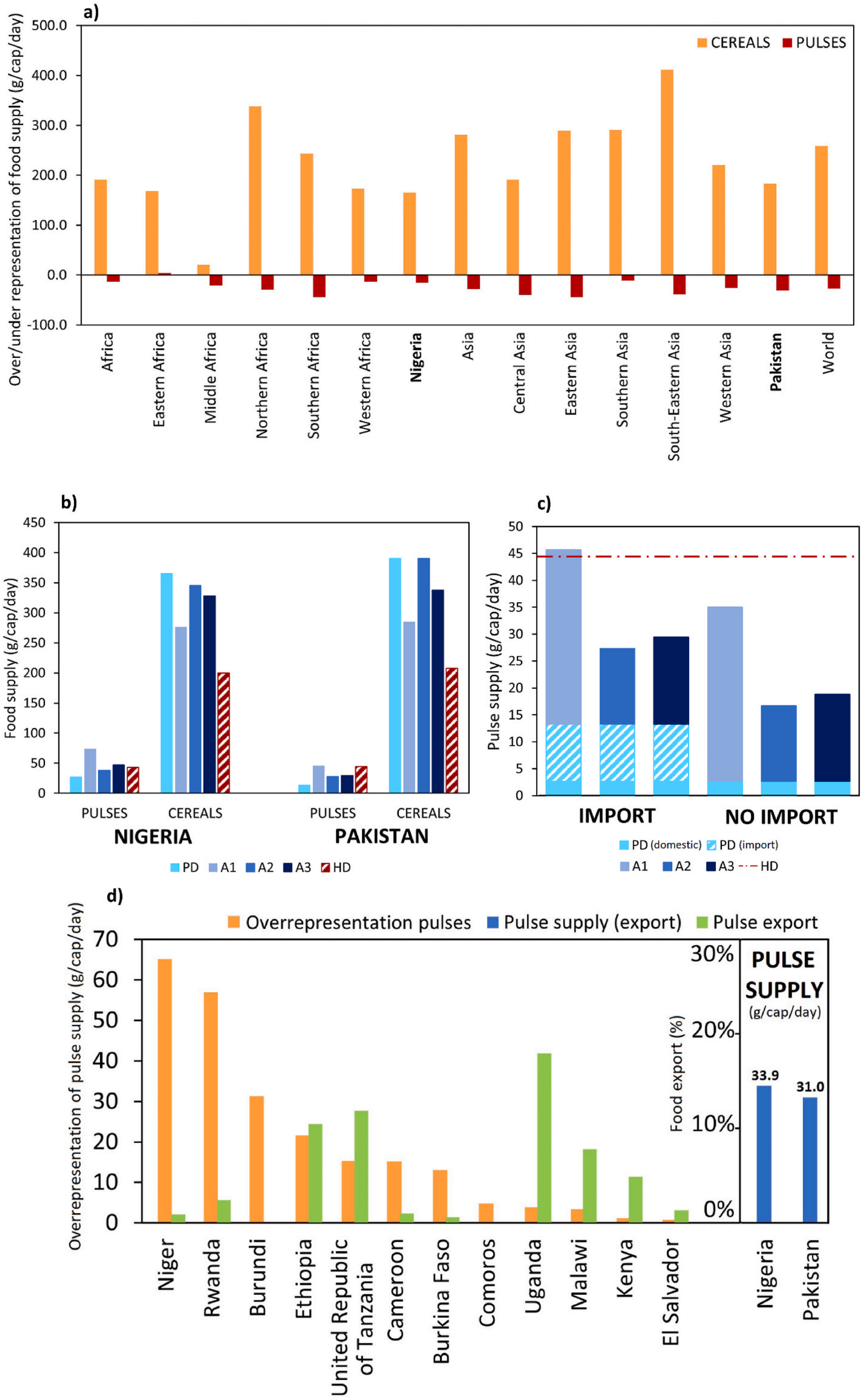

**Fig. 1.** a) Over/under representation of cereals and pulses in diets computed as the difference between the region-specific present diet net of waste (PD) and the corresponding healthy diet (HD) in grams per capita per day; Fig. 1 – b) Dietary supply of pulses and cereals in g/cap/day for the three scenarios (A1, A2, A3) of crop replacement in Nigeria and Pakistan, compared with present diet net of waste (PD) and the country-specific healthy diet (HD); Fig. 1 – c) Dietary supply of pulses in g/cap/day in Pakistan accounting for supply coming from present scenario domestic production (PD (domestic)) and import (PD (import)) and the supply coming from the three scenarios (A1, A2, A3) of crop replacement, compared with the country-specific healthy diet (HD) in Pakistan; Fig. 1 – d) Pulse supply in g/cap/day for all the countries showing overrepresentation of pulses in diet (orange), their corresponding share of pulse export over total production (green), and pulse supply net of waste (blue) in g/cap/day achievable by boosting trade from surplus countries to either Pakistan or Nigeria.

recommended amount from the EAT-Lancet Commission (i.e., 32%) (Fig. S2). The daily energy supply from legumes (i.e., pulses, soybeans and groundnuts) instead contributes to less than 10% of the total daily calories of present diet (way lower than the EAT-Lancet recommended intake of 17%) (Fig. S2). Moreover, Pakistan has the lowest caloric supply of pulses, while cereals are overrepresented in both countries (Fig. 1).

Overall, Nigeria and Pakistan are two representative case studies of all Asian and African regions (except for Eastern Africa) (Fig. 1a). As a result, this procedure can be applied also to other countries within these regions, especially where cereals are mainly domestically produced (e.g., Western Africa, Southern and Eastern Asia) (Fig. S3) and so replacement can happen locally rather than redirecting import.

We find that crop replacements allow for an increase in the overall net pulse (hence, iron) availability (i.e., production minus waste and losses) especially in scenario A1 in Nigeria (Fig. 1). However, in some cases, the replacement scenarios fail to meet the requirements for a healthy diet recommended by the EAT-Lancet Commission, as observed in scenario A3 (i.e., no monoculture of pulses) in Pakistan or in scenario A2 (Fig. 1). The increase in pulse supply in Pakistan is still substantial, even though in scenarios A2 and A3 it does not reach the recommended values of the healthy diet. Conversely, cereal supply decreases, though still showing overconsumption compared to the healthy diet from the EAT-Lancet Commission (Fig. 1). This happens because the remaining areas harvested with cereals are not suitable for pulse cultivation and so cannot be used for pulse production. This result suggests that it could be possible to make additional substitutions of cereals with pulses to further improve the supply of pulses (and associated micronutrients). However, crop replacement is here clearly limited by the availability of suitable land for pulse replacement. For example, in Pakistan, pulse supply meets healthy recommendation in scenario A1 when accounting for both present pulse supply from import and domestic production (Fig. 1 right). In the absence of the current pulse supply from import, pulse supply in Pakistan would fail to meet the healthy diet recommendations even in scenario A1 (Fig. 1 right). However, this is not the case for Nigeria where pulse consumption comes entirely from domestic production (FAOSTAT, 2019a).

Nevertheless, pulse supply can also increase by redirecting trade to either Pakistan or Nigeria from countries showing overrepresentation of pulses in their diet compared to EAT-Lancet recommendations. We found that globally only 11 countries show surplus of pulses (orange bars in Fig. 1d) which, in turn, can help ensure pulse supply net of waste either in Nigeria or in Pakistan of 33.9 and 31.0 g per capita per day, respectively (blue bars in Fig. 1d). However, this can happen only by boosting trade in such countries, since current share of export of pulses over total production (green bars in Fig. 1d) is very low (around 10%). In the case of trade redirection, exporter countries in Fig. 1d would still have a healthy diet despite the export of pulses. In turn, when changing trade routes, current exporters to Pakistan (e.g., India, China, Australia) could see their food supply increase and so improve their nutritional status.

Overall, when shifting from present diet to the scenarios A1, A2, and A3, the availability of pulses increases in both countries, while water consumption decreases (Figs. 1–3). The monoculture scenario (A1) achieves the greatest dietary pulse production along with the highest water saving (Figs. 1–3), and meets the EAT-Lancet recommendations in all the countries. Moreover, in the case of Pakistan, the replacement of cash crops (scenario A2) leads to the fulfillment of the EAT-Lancet recommendation, while leaving grain consumption unaltered (Fig. 1). Overall, according to the crop replacement scheme adopted in this study, the replacement takes place mostly in rainfed areas of Nigeria cultivated with cereals, while in Pakistan crop replacement affects irrigated areas. Therefore, we attain green water savings in Nigeria, and blue water savings in Pakistan (Fig. 2). To appreciate the magnitude of these water savings we also express them as a fraction of the current water consumption in these areas (Fig. 3). We find that in the monoculture scenario Nigeria's green water savings are 27% and Pakistan's blue water savings are 31%, without showing significant green water savings. Both blue and green water savings may have important positive impacts on water availability for downstream users and environmental flows. Accordingly, grey water is higher in cereals while lower in pulses because of the lower (or zero) rates of nitrogen application (Table S1). Moreover, crop replacement affects millions of hectares in Pakistan and Nigeria (Table 1 and Fig. S1), particularly in the scenario A1.

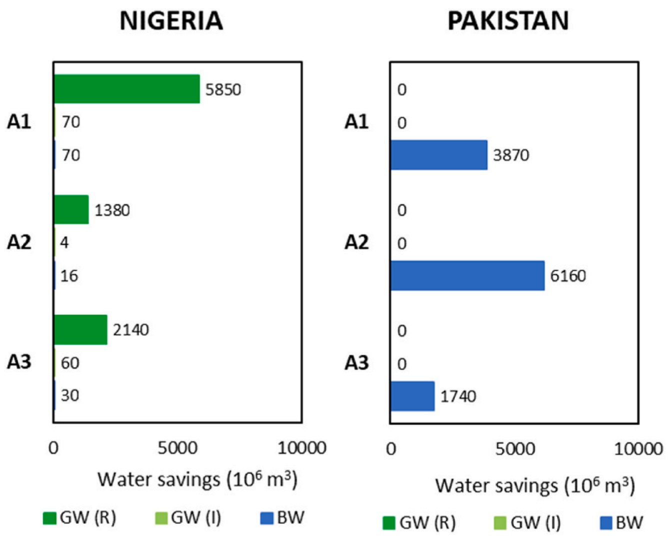

**Fig. 2.** Water saving in volume ($10^6$ $m^3$) when shifting from the present diet to the three scenarios, A1, A2, and A3, in Nigeria and Pakistan. Water saving are calculated both for green water (GW) and blue water (BW). GW savings refer both to rainfed (R) and irrigated areas (I).

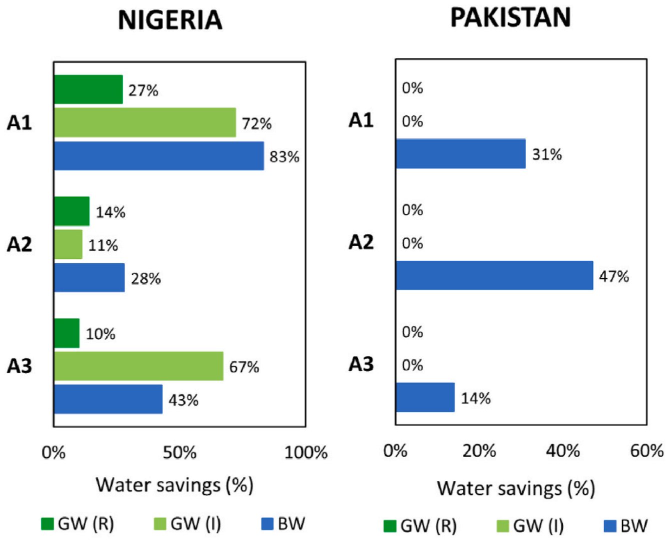

**Fig. 3.** Water saving in percentage (%) when shifting from the present diet to the three scenarios, A1, A2, and A3, in Nigeria and Pakistan. Water saving are calculated both for green water (GW) and blue water (BW). GW savings refer both to rainfed (R) and irrigated areas (I).

Results (Fig. 1, Table 1) show that in both countries it is possible to close the pulse gap in consumption between the present and the recommended intake in the case of monoculture (Scenario A1). For Nigeria, we find the highest water savings in scenario A1, along with the lowest pulse gaps. A shift from scenario A1 (i.e., monoculture) to scenario A3 (i.e., no monoculture) would increase the gap in pulse consumption to

**Table 1**

Harvested areas ($10^6$ ha) reallocated to pulses production from cereals/cash crops and corresponding pulse gap for the three scenarios (A1, A2, A3) and present diet (PD) in Nigeria and Pakistan.

| Country | Replaced areas ($10^6$ ha) | | | Pulse gap | | | |
|---|---|---|---|---|---|---|---|
| | A1 | A2 | A3 | PD | A1 | A2 | A3 |
| NIGERIA | 4.0 | 0.9 | 1.7 | 37 % | 0 % | 13 % | 0 % |
| PAKISTAN | 2.8 | 1.3 | 1.5 | 70 % | 0 % | 39 % | 34 % |

about 34% in Pakistan. Thus, a redistribution scheme without pulse monoculture (scenario A3), allows for pulse gap closure only in Nigeria. Even in the most restrictive case (scenario A3) that avoids monocultures, we find that Nigeria can almost meet the country-specific healthy diet recommendations, so reducing its pulse gap to 7% and 0% in the A3 and A1 scenarios, respectively. Starting from 70% pulse gap for Pakistan and 37% pulse gap for Nigeria in the present diet (PD), A1 and A3 scenarios allow for substantial pulse gap reduction (Table 1).

When accounting for the possible increase in food supply through trade redirection, we find that it could be more water and land intensive than current trade in Pakistan (Table 2). While, currently, for producing around 10 g/cap/day of pulses (Fig. 1b) are needed 0.7 million hectares and more than 2 $km^3$ of water, in the case of trade from surplus countries, for producing 30 g/cap/day of pulses are needed 5 million hectares and nearly 20 $km^3$ of water.

Overall, micronutrient availability increases from present diet scenario to the three A1, A2, and A3 scenarios in both Countries. This implies reducing, to a certain extent, the current micronutrient inadequacies in diet (i.e., expressed as the difference between micronutrient intake from PD and RNI or EAR). This is especially true in Pakistan where the dietary inadequacies in potassium, thiamin, riboflavin, and folate can be considerably reduced and, in some cases, eradicated (Fig. 4). For example, while current thiamin, riboflavin and niacin intake already meet their corresponding EAR in Pakistan, their increased availability in A1 and A2 is able to meet also RNI, especially for thiamin (Fig. 4 – green and blue bars). Moreover, the current dietary inadequacy (EAR) in folate can be completely eliminated in A1, while it can be met up to around 60% in A2/A3 (Fig. 4 – blue bars). However, when considering the RNI as reference intake, A1 and A2/A3 scenarios can meet just up to 60% and 40% of current folate inadequacy (RNI), respectively (Fig. 4 – green bars). Folate deficiency can directly cause anemia, neurological issues, and complications during pregnancy, while vitamin Bs deficiency in general is linked to mental impairment and limited iron absorption (Tulchinsky, 2010). Regarding Nigeria, A1 scenario could meet up to 80% and 30% of the current inadequacy in choline with EAR and RNI as reference, respectively. Lastly, the current inadequacy in zinc, calcium, iron can be fulfilled up to around 10%–20% in both Countries. While iron deficiency is known for inducing anemia, inadequate zinc intake can cause malfunctions in the immune systems and insufficient intake of calcium can lead to osteoporosis (Tulchinsky, 2010; Wessells and Brown, 2012). Overall, dietary inadequacies for RNI are more difficult to meet compared to EAR inadequacies because RNI recommendations are stricter (and so higher) compared to the EAR requirements.

Moreover, as far as iron availability is concerned, we find that the present diets (PD) fail to meet the healthy iron recommendations for pulses in these countries (Fig. 5-green bars). We also notice that iron recommendations for meat are almost fulfilled in Nigeria (Fig. 5-red bars), even though its population is currently suffering from anemia. Indeed, the fact that in a population the iron supply is on average sufficient to meet the demand does not mean that every person in that population has access to adequate iron supply. Moreover, in Nigeria, several other morbidities are affecting the population (i.e., malaria and gastrointestinal diseases) with the effect of exacerbating anemia. Thus, crop replacement will increase iron supply and could improve intake within the population, but the effectiveness of the intervention is strictly dependent on comorbidities of other diseases.

**Table 2**

Harvested areas (in $10^6$ ha) and virtual water trade (in $km^3$) for the scenario with export from countries showing overrepresentation of pulses in diets (i.e., trade scenario) and comparison with current export to Pakistan.

| TRADE SCENARIO | | CURRENT TRADE (PAKISTAN) | | |
|---|---|---|---|---|
| LAND ($10^6$ ha) | GW ($km^3$) | LAND ($10^6$ ha) | GW ($km^3$) | BW ($km^3$) |
| 5.1 | 18.8 | 0.7 | 1.8 | 0.3 |

As expected, dietary iron intake from pulses increases while iron intake from cereals decreases in all scenarios (Fig. 5). After crop replacement, Nigeria increases iron availability from pulses to values comparable to the healthy diet requirement, while Pakistan fails to meet the healthy diet recommendations in all the scenarios included in this study (Fig. 5). Moreover, iron intake from meat is low in Pakistan and Nigeria (Fig. 5), potentially reducing iron absorption from plant-based sources (e.g., pulses).

Moreover, protein and caloric intake satisfies the healthy diet recommendations from EAT-Lancet in all scenarios for these countries (and it comes close to fulfilling such recommendations with present diets) (Figs. S4 and S5).

Currently, in both countries cereals have relatively high yields and low producer prices while pulses have relatively low yields and high producer prices (Fig. S6). Although producing pulses costs less than producing cereals, the profits from cereals are comparable to the profits from pulses, as shown in Fig. 6 and in detail in the supplementary economic analysis (Fig. 6, S7, S8, S9).

## 4. Discussion

Sustainable agricultural changes to address dietary needs and human well-being are a major global challenge of our time that must simultaneously address environmental and human health goals. In this study, we focus on agricultural strategies to sustainably increase the intake of micronutrient-rich food in local diets and consequently reduce the prevalence of micronutrient deficiencies. Previous studies have shown that crop replacement can help achieve more sustainable diets (Davis et al., 2017, 2018; Damerau et al., 2020; Miller et al., 2003; Yang et al., 2021) locally, and that pulse consumption improves dietary quality (Iriti and Varoni, 2017; Singh, 2017). We replace crops in countries where pulses are socially acceptable because they are part of the local culinary tradition and are already produced there, though in smaller quantities (FAOSTAT, 2019a). Our proposed crop replacement strategy can improve human health in two ways. On the one hand, it reduces the consumption of cereals to healthy levels according to the guidelines of the EAT-Lancet Commission (Willett et al., 2019). On the other hand, it increases micronutrient intake, thus counteracting micronutrient inadequacies in the diet. Nevertheless, the extent to which this sustainable diet can meet human micronutrient requirements is still debated (Beal et al., 2023). Overall, micronutrient availability in diets increases especially for iron, folate, vitamin Bs, and potassium particularly in Pakistan. This is particularly significant since the prevalence of iron and folate deficiencies are higher in low-to-middle income countries and can lead to anemia and neurological impairment (Tulchinsky, 2010; WHO, 2015; Harika et al., 2017). Here, we find that the replacement of excess cereal production with pulses would be able to close the current dietary iron gap in Nigeria without intensification of crop production while the iron requirements are almost met in Pakistan only with intensified pulse production. These crop replacement scenarios allow for water savings, while keeping the same spatial extent of cropland and reducing local crop diversity (i.e., at the pixel scale of 10 km).

Our results also show that the wheat-rice systems of Pakistan can be replaced with more sustainable and diversified cropping systems involving pulses. Beside reducing water use compared to cereals, pulses

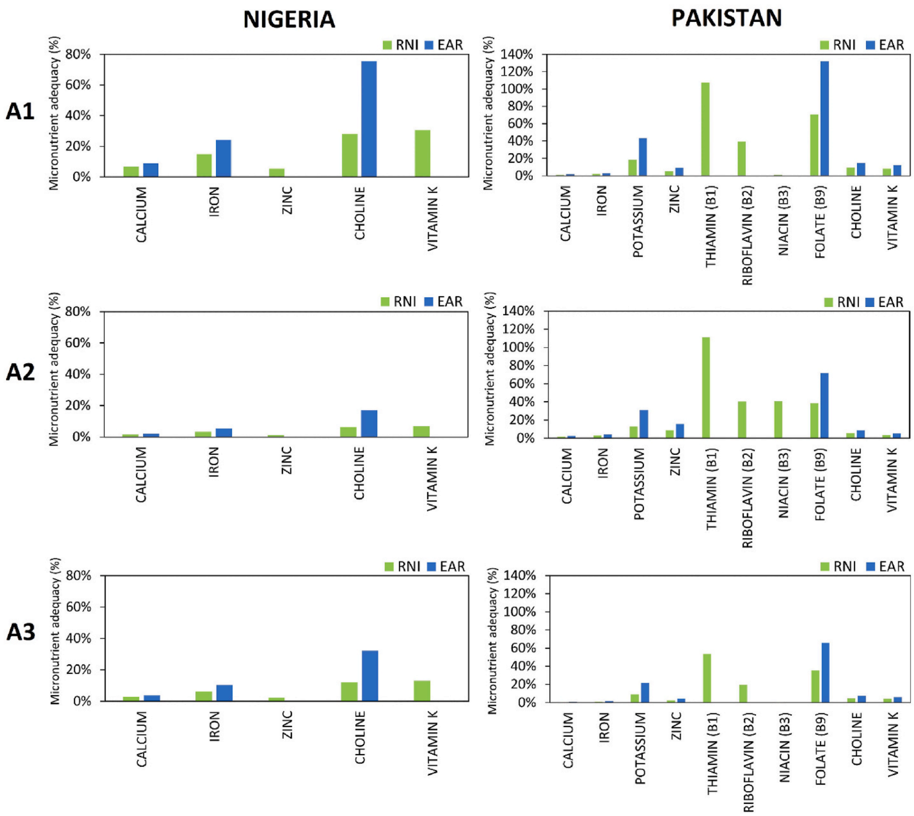

**Fig. 4.** Micronutrient adequacy of crop replacement scenarios in Nigeria and Pakistan for each scenario A1, A2, A3 computed as the ratio (in %) between the increase in micronutrient availability from present diet (PD) and the current micronutrient inadequacy in diet (PD) (i.e., the difference between micronutrient intake from PD and the Reference Nutrient Intake (RNI) or the difference between micronutrient intake from PD and the Estimated Average Requirement (EAR)).

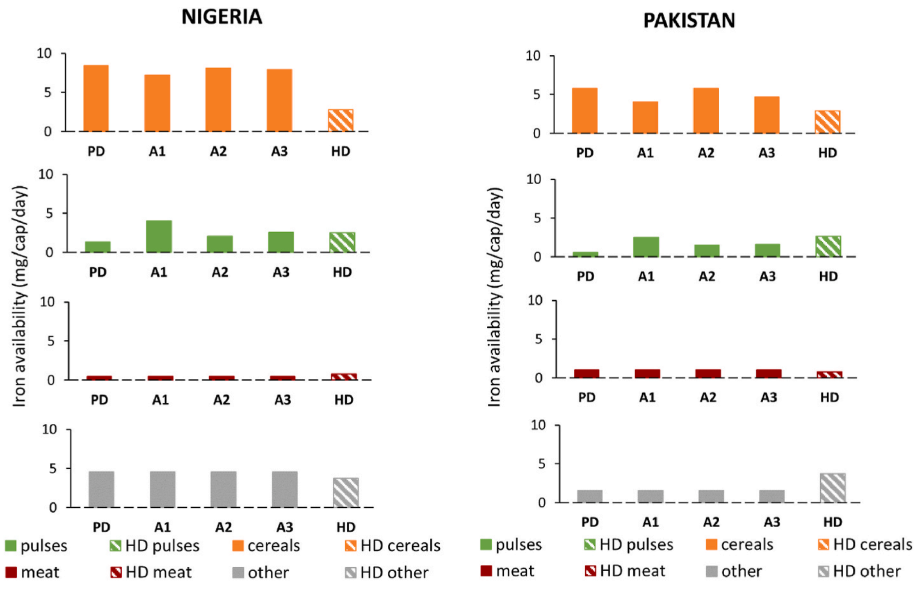

**Fig. 5.** Change in iron availability from present diet scenario (PD) to replacement scenarios (A1, A2, A3) for cereals, pulses, meat and other food compared to the healthy recommendations (HD) from (Willett et al., 2019) in Nigeria and Pakistan.

are nitrogen fixers that enhance the availability of reactive nitrogen in the land where they are cultivated, thus boosting crop yields (Mudryj et al., 2014; Miller et al., 2003; Lal and Sparks, 2017; Peoples et al., 2009; Liu et al., 2020). However, because pulses typically attain smaller yields than cereals, crop replacement allows for only a modest increase in pulse supply while substantially reducing cereal production (without dropping cereal supply below the recommended intake level). This can, in turn, dramatically increase the price of cereals and so reduce the feasibility of crop replacement. Although intensification substantially increases pulse production, in Pakistan the dietary needs for iron cannot be completely met by shifting from grain to pulse production within the current extent of agricultural areas.

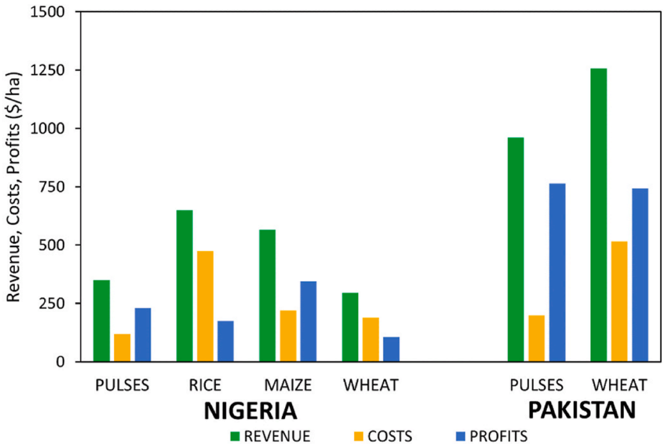

**Fig. 6.** Revenue, costs, and profits in $/ha for cereals (e.g., rice, maize, wheat) and pulses in Nigeria and Pakistan under current yield from SPAM2010 (Spatial Production Allocation Model) (Yu et al., 2020) (see Supplementary Materials).

The relatively low yield of pulses is problematic also for the economic feasibility of the proposed crop shifts. Will farmers be able to achieve comparable (or greater) profits by shifting from grain to pulse production? Farmers choices related to crop production depend on whether the country's economy is based on subsistence or commercial agriculture. While Pakistan relies on domestic commercial agriculture, Nigeria depends mainly on small scale subsistence farming (Apata et al., 2011). In Pakistan small-scale farmers still account for more than half of the cultivated area and the country has a well-established internal food market relying on staple and cash crop production as well as governmental subsidies (Government of Pakistan, 2010; Khan, 2020). While for most part subsistence farmers cultivate the food they eat, commercial farmers choose the crops they cultivate, depending on the profit that can be generated (i.e., by balancing production costs and revenues) (Greig, 2009). To be feasible, a shift in crop production should preserve or enhance farmers' profits, while providing affordable food to the consumers.

Even though production costs are lower for pulses than cereals, part of these costs are often subsidized. However, the low yield of pulses constrains their ability to generate revenues, which are low when compared to cereals (Rawal and Navarro, 2019). Currently, pulses are known for being not competitive compared to other staple crops (e.g., wheat and rice) in food markets (Abraham and Pingali, 2021).

To be widely adopted, pulses need to be more competitive in the market, which means that their yields need to be enhanced, likely through intensified production that closes the gap existing between actual and potential yields. Intensification often occurs through an agrarian transition from small scale farming to large scale commercial agriculture and the associated increasing reliance on technological inputs such as agrochemicals, machineries, and irrigation. For instance, in Australia and Brazil the yields of pulses were increased by the adoption of technological inputs in large farms, which made pulses competitive on the market (Rawal and Navarro, 2019).

However, in Pakistan, where the government regulates the agricultural market, a shift to pulse production can be hindered by preexisting government interventions (e.g., subsidies and minimum support prices for cereals) (Rawal and Navarro, 2019). For example, pulse production in Pakistan is constrained by government incentives to cereal production (i.e., procurement practices, subsidies for inputs and export tax) (ACIAR, 2019). Present regulations directly favor the production of staple crops such as wheat through minimum procurement price (i.e., purchase price set by the Government) and indirectly through subsidies on fertilizers which are not particularly needed for pulse production (ACIAR, 2019). While the introduction of similar procurement prices for pulses can potentially increase pulse production, it can turn out to be costly for the Government (ACIAR, 2019).

Overall, a shift from cereals to pulses requires not only improved profits, but also better access to a food market to place these crops (Lencucha et al., 2020). Thus, the neoliberal economics of pulse production (e.g., large private agribusiness, free markets, displacement of smallholders) could ensure the attainment of the production levels needed to achieve nutritional food security, though it could also run subsistence farmers and smallholders out of business. The associated loss of rural livelihoods could negatively impact the economic access to nutritious food.

Overall, it could be difficult to convince farmers to shift from cereals to pulses without substantial changes in governmental policies and without changing consumers' demand. From the consumer's perspective, prices of healthy food such as pulses can be another significant obstacle to their consumption particularly by the less affluent classes in regions where food is predominately produced by commercial agriculture (FAO et al., 2020). Staple crops (i.e., cereals) have the lowest costs compared to other food groups, and the price difference plays an important role in consumer choices in low-income countries (Springmann et al., 2021). Thus, economic access to pulses is more limited compared to cereals. According to the Bennett's law, the proposed crop replacement can be feasible in the case people are willing to pay more for nutrient-dense food and can afford to do so (e.g., rich households). In turn, this will less likely happen in poor households who barely make ends meet and won't be able to buy pulses to diversify their diet, which will remain unaltered despite the implementation of the crop replacement.

However, an increase in the production of pulses could lead to a decrease in their prices, thereby improving their affordability, while decreasing farmers' profits. In many cases (e.g., South Asia), staple crop prices are also set by Government interventions to improve food access in poor households (Dorosh, 2009; Dorosh and Salam, 2008). For example, during the last century food policies have used subsidies to promote the production of staple crops in South Asia and consequently reduced malnutrition (Pingali, 2015). This approach, however, has caused, micronutrient deficiencies within the population (Pingali, 2012, 2015). Currently, some countries have been trying to adopt new food policies promoting healthy food production (Government of Pakistan, 2018; Li et al., 2020). Shifting towards healthier diets requires the promotion of both sustainable production and the consumption of healthier food such as pulses (Lencucha et al., 2020). Policies promoting the adoption of healthy diets among consumers include nutritional labeling, nutritional education (Roberto et al., 2014; Brambila-Macias et al., 2011), taxation of unhealthy food (World Health Organization, 2015), healthy meal programs at school and nutrition awareness among younger people (Brambila-Macias et al., 2011) who are particularly affected by anemia worldwide (Thompson, 2007). The actual adoption of healthy diets by a population, however, can also be impeded by lack of adequate knowledge of nutritional needs (Ali and Rahut, 2019). Thus, effectively addressing micronutrient deficiency should also focus on increasing people's awareness of healthy diets and the associated benefits to human wellbeing (Akhtar et al., 2013). This is particularly relevant in the case of subsistence agriculture because in this case farmers are both producers and consumers. Thus, crop production can be more easily reoriented based on sustainable diets awareness and achievable yields (Greig, 2009). For example, in Nigeria, where more than half of the farmers depends on subsistence farming (Apata et al., 2011), pulse production and consumption can be more easily reoriented locally by increasing people's awareness of the benefits of sustainable diets while promoting agroecological practices to enhance pulse yields.

Moreover, a reduction in the prevalence of nutritional diseases (such as anemia) requires the intake of bioavailable nutrients (e.g., iron). For example, iron in plant-based food tends to exhibit low bioavailability (Kotecha, 2011; Shubham et al., 2020; Hallberg and Hulthén, 2000; Hurrell and Egli, 2010), while it is found in low amounts and with high bioavailability in red meat (between 10 and 25%) (Hallberg et al., 1979). Legumes and vegetables (e.g., spinach) have high iron content but relatively low bioavailability (around 1–2%), though higher than cereals (Suliburska and Krejpcio, 2014; Hemalatha et al., 2007; Cook and Juillerat, 1997; Lynch et al., 1984). Thus, compared to cereals, pulses offer a more valuable source of iron as well as of micro- and macronutrients (e.g., folate, zinc, vitamin Bs) (Singh, 2017). Moreover, pulses (as opposed to cereals) are also a well-known source of plant ferritin which captures and stores iron and, in turn, can prevent iron deficiency (Zielińska-Dawidziak, 2015). A shift to higher quality diets (i.e., with higher rates of pulse consumption) can overall improve human health. However, the impact on the prevalence of nutritional anemia can be limited by the overall low bioavailability of iron in plant-based sources, compared to meat.

In addition to increasing the intake of micronutrient-rich food, a comprehensive healthy diet aiming at reducing the prevalence of micronutrient deficiencies should also account for nutrient absorption. For example, to increase iron absorption, dietary shifts need to enhance the intake of both iron-rich food products, such as pulses, as well as micronutrients that are essential to iron bioavailability (Willett et al., 2019). Therefore, food rich in vitamin C (i.e., ascorbic acid), such as citrus, should be consumed along with legumes to increase overall iron absorption from plant-based sources (Shubham et al., 2020; Hallberg and Hulthén, 2000). Conversely, the intake of food inhibiting iron absorption (e.g., tea and coffee) should be limited (Hallberg and Hulthén, 2000). For example, the low intake of fruits and vegetables in Pakistan and the high tea consumption (FAOSTAT, 2019a) can concur to this country's high levels of iron deficiency anemia incidence. Food types that can serve as enhancers of iron absorption (e.g., meat and fruits and vegetables rich in vitamin C) are consumed in low quantities both in Pakistan and Nigeria (FAOSTAT, 2019a) (Fig. 5). Moreover, diet diversification should be coupled with iron fortification or supplementation to effectively control anemia (Shubham et al., 2020; Haas et al., 2016). For example, legumes can also be fortified by adding iron to further increase iron intake, especially in countries affected by nutritional anemia (Haas et al., 2016; Mutwiri et al., 2020).

Micronutrient inadequacies reveal the overall risk of micronutrient deficiencies among the population, but the effective prevalence of diseases can be assessed only using cutoffs for biomarkers through blood analyses (Hess et al., 2021). Therefore, empirical cohort studies that locally assess the actual increased nutritional status of the population should follow the adoption of agricultural interventions aiming at improving dietary quality. Our findings show the extent to which it is biophysically possible to sustainably adopt dietary improvements that reduce the prevalence of nutritional anemia while saving water, but further research is required to capture the other social, cultural, and economic factors involved in dietary changes.

## Declaration of competing interest

All authors have nothing to disclose.

## Data availability

Data will be made available on request.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gfs.2023.100734.

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