Exposure and Health
https://doi.org/10.1007/s12403-024-00634-8

ORIGINAL PAPER

Human Health Impact Based on Adult European Consumers' Dietary Exposure to Chemical Contaminants and Consumption of Unprocessed Red Meat, Processed Meat, and Legumes

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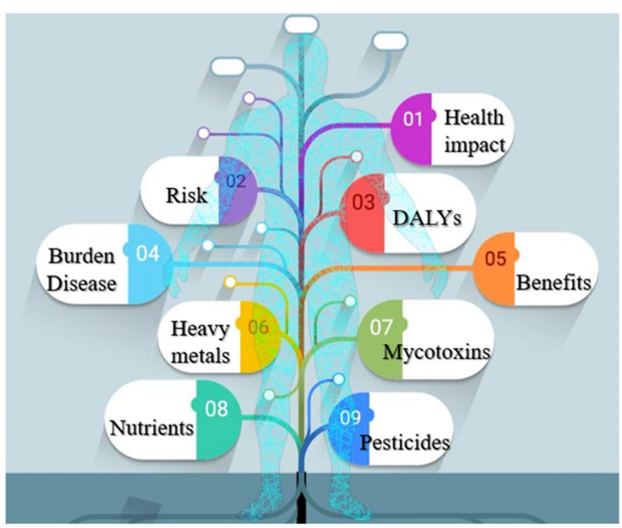
Received: 27 November 2023 / Revised: 8 February 2024 / Accepted: 9 February 2024

Abstract

In this study we assessed the human health impact based on dietary trends for adult consumers in Europe. The risk of ten illnesses was estimated based on dietary exposure to inorganic arsenic, lead, cadmium, aflatoxin B1, and pesticides and consumption of unprocessed red meat, processed meat, and legumes (reference scenario (RS)) and a simulated alternative scenario of legumes consumption only (AS). Nutrient adequacy per each diet was estimated for vitamin B12, zinc, iron, and selenium. The burden of disease was quantified using Disability-Adjusted Life Years (DALYs). The potential health risk and DALYs differ when comparing the burden due to exposure to chemical contaminants and the burden from the consumption of food, the former favoring the RS, while the latter favors the AS. The burden of disease due to exposure to chemical contaminants was between 672,410–1,215,875 DALYs in the RS, while in the AS it was between 964,132–1,084,229 DALYs. Consumption of processed meat added up to 1,813,338 DALYs, while legume intake averted 364,973 DALYs. However, the AS also indicated lower nutrient intakes potentially increasing the risk of nutrient inadequacy. A balanced diet made up of a variety of different foods is essential to prevent potentially higher dietary exposures to a range of chemical contaminants and assure adequate micronutrient intake. Greater importance should be given to food consumption trends and cross-referenced to existing and new natural toxin legislation and risk assessments in view of the ubiquitous and growing occurrence of heavy metals and mycotoxins in our food. The impacts of climate change, and the growing tendency toward plant-based diets are two factors which will drive further increases in human exposure to toxic contaminants.

Graphical Abstract



Extended author information available on the last page of the article

Keywords Dietary exposure · Burden of disease · DALY · Health impact · Dietary patterns · Plant-based diet

Introduction

Chemical contaminants found in foods rank as the third most important foodborne public health concerns in Europe. If their occurrence is not kept below levels as prescribed by law, they can represent a risk to public health (Eskola et al. 2020).

Based on a recent risk ranking and available data for conclusive endpoints, among the chemical contaminants that can pose health risks for adult European consumers due to chronic dietary exposure are heavy metals such as cadmium (Cd), arsenic (As), and lead (Pb), pesticides, and aflatoxins which are genotoxic and carcinogenic mycotoxins known to cause human liver cancer (Schrenk et al. 2020).

Consumers' dietary exposure to chemical contaminants is dependent on the levels of contamination present in particular foods and their individual dietary habits. Nowadays, due to a range of highly important planetary and human health concerns, recommendations are being made to reduce the consumption of unprocessed and processed red meat and to shift toward plant-based diets (Bunge et al. 2022; Willett et al. 2019).

Consumption of processed meat has been shown to be one of the causes of colorectal cancer (CRC) and ischemic heart disease (IHD) (Papier et al. 2021), which is mainly due to the use of nitrites added during processing (Bouvard et al. 2015; Schrenk et al. 2023). However, recent studies have shown weak to no significant correlations for the risk of type 2 diabetes (T2D) and IHD (Lescinsky et al. 2022). Furthermore, research shows that plant-based diets bear a number of risks associated with micronutrient inadequacies (i.e., vitamin B12 is absent in plants, lower iron intake, etc.) (Pellinen et al. 2022). Among micronutrients, vegans and vegetarians are at risk of vitamin B12, zinc, iron, and selenium deficiencies which can potentially lead to adverse health effects such as iron deficiency anemia, growth impairment, and neurological and gastrointestinal symptoms (Wolffenbuttel et al. 2019).

While legume consumption can reduce the risk of IHD (Afshin et al. 2014), recent studies have reported that changing toward plant-based meat analogs can lead to an increased exposure to natural contaminants when compared to an omnivore diet (Mihalache et al. 2022; Penczynski et al. 2022). Among contaminants reported to occur in legumes, only pesticides and cadmium are currently regulated (European Commission, 2006). Other contaminants such as arsenic, lead, and mycotoxins have no regulatory limits.

We have considered meat consumption in an omnivore diet (reference scenario (RS)), and the simulation of replacement of meat with legumes in a vegan/vegetarian diet (alternative scenario (AS)). The objectives were to assess the potential burden of disease caused by (i) selected chemical contaminants in foods and (ii) the consumption of unprocessed red meat, processed meat, and legumes, and quantify the results using Disability-Adjusted Life Years (DALYs).

Thus, the aim was to assess the human health impact for adult European consumers due to the ongoing shifts in diets.

The results from this study provide an important starting point to highlight the need for a robust, evidence-based regulatory framework of selected chemical contaminants in plant-based foods and showcase the transition in exposure to contaminants concurrent with the shifts in diets.

Materials and Methods

Human health impact from dietary exposure to chemical contaminants was assessed in a reference scenario (RS), which has a diet containing unprocessed red meat, processed meat, and legumes and in a simulated alternative scenario (AS) with a full replacement of meat with legumes. We first collected data regarding the contamination of these food items with i-As (Arcella et al. 2021), Pb (EFSA 2012a), Cd (EFSA 2012b), pesticides (Anastassiadou et al. 2021; EFSA and Dujardin 2021), and aflatoxin B1 (AFB1) (Schrenk et al. 2020). Chronic food consumption data were retrieved from the European Food Safety Authority (EFSA) food consumption database.

Identification of Adverse Health Effects

Chemical Contaminants in Food

Recent reports from EFSA with data from multiple European countries show that legumes are contaminated with AFB1. This mycotoxin is classified by the International Agency for Research on Cancer (IARC) as a group 1 carcinogenic agent to humans (IARC 2019).

IARC also classified As and i-As compounds as group 1 carcinogenic agents to humans (IARC 2019). i-As is considered to be more toxic than the organic form and chronic exposure is known to cause lung, bladder, and skin cancer (Arcella et al. 2021).

Pb exposure is associated with CVD and IHD mortality (Lanphear et al. 2018), while Cd accumulation has adverse effects on human health, including coronary heart disease (CHD) and stroke (Fagerberg and Barregard 2021).

In 2019, EFSA established different cumulative assessment groups (CAGs) of pesticides for adverse health effects.

In this study, we will highlight the groups of pesticides that can cause the following:

- Chronic acetylcholinesterase inhibition (CAG-NCN) (47 active substances out of which 11 are organophosphates and 36 are N-methyl carbamates) (Anastassiadou et al. 2021);
- Hypertrophy, hyperplasia, and neoplasia of C-cells (CAG-TCP) (18 pesticides) (EFSA and Dujardin 2021); and
- Hypothyroidism (CAG-TCF) (124 pesticides) (EFSA and Dujardin 2021).

Consumption of Processed Meat

Based on its association with colorectal cancer (CRC), processed meat is categorized by IARC as a group 1 carcinogenic agent to humans (IARC 2019).

There is strong evidence from randomized trials and observational research that high consumption of processed meat increases the risk of chronic illnesses like IHD and T2D (Papier et al. 2021).

Therefore, only data for the consumption of processed meat were used to estimate the potential risk of CRC, IHD, and T2D.

Identification of Beneficial Health Effects

Decreased Risk of Iron Deficiency Anemia (IDA)

Consumption of red meat has beneficial effects due to its nutritional characteristics, especially as a source of heme iron. Iron intake lowers the risk of iron deficiency and, subsequently, anemia (Czerwoanka and Tokarz 2017; Papier et al. 2021), therefore the health benefit associated with consumption of unprocessed read meat in this study is that of potentially reducing iron deficiency anemia.

Decreased Risk of Ischemic Heart Disease (IHD)

Legume consumption is associated with a decreased risk of IHD (Afshin et al. 2014), while the reduction of risk of T2D is conflicting (Tang et al. 2020). Hence, the beneficial effect from legume consumption taken into consideration in this study is the decreased risk of IHD.

Decreased Risk of Prostate Cancer (PC)

Selenium (Se) can be found in meat as well as in legumes. According to the report from the World Cancer Research Fund (WCRF), higher Se levels are correlated with a lower risk of prostate cancer (WCRF 2018), therefore the potential cancer risk reduction based on Se intake will be investigated.

Nutritional Intake

Red meat is one of the main sources of heme Fe, Zn, Se, and vitamin B12, while legumes are substantially less rich in Zn, Se, and do not contain vitamin B12. Several studies reported lower vitamin B12 intake and risk of inadequacy in vegan (Elorinne et al. 2016) and vegetarian diets (Fallon and Dillon 2020), lower Fe stores in vegetarians due to the low bioavailability of non-heme Fe from plants (Sliwinska et al. 2018), and lower Zn and Se intakes in vegan and vegetarian diets (Fallon and Dillon 2020; Tong et al. 2019).

For these reasons, we estimated the intake of these four nutrients in the RS with unprocessed red meat, processed meat, and legumes consumption and in the simulated AS with consumption of legumes only.

Food Consumption Data

The food consumption data were retrieved from the EFSA food consumption database, which has the latest National Food Consumption Surveys from: Austria, Belgium, Bosnia and Herzegovina Montenegro, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Netherlands, Portugal, Romania, Serbia, Slovenia, Spain, Sweden, and the United Kingdom. Based on the type of food, the total number of adult consumers varied between 11,017 (for legumes) and 25,086 (for unprocessed/processed meat). The cross-sectional surveys were conducted using consecutive three-day food records. In this study, we took into account only consumption data for adults. This was also to minimize variability and uncertainty in the final burden of disease estimations.

Problem Formulation and Exposure Scenarios

The purpose of this study was to model the human health impact for adult European consumers based on food consumption and chronic exposure to chemical contaminants in a reference scenario (RS) with consumption of unprocessed red meat, processed meat, and legumes and a simulated alternative scenario (AS) with legumes consumption only.

The exposure scenarios were assessed using occurrence data from EFSA reports (Arcella et al. 2021; EFSA 2012a; EFSA 2012b; Schrenk et al. 2020). Based on the recommendations from EFSA, two types of exposure scenarios were taken into consideration: optimistic scenario (OS) using the mean lower bound (LB) contamination values and the pessimistic scenario (PS) using the mean upper bound (UB) contamination values. For both scenarios the chronic exposure was calculated using the Dietary Exposure (DietEx) tool from EFSA.

Risk of Nutrient Inadequacy

The nutritional intakes were assessed using data from EFSA's Food Composition Database. We used the average requirement (AR) for Fe and Zn and adequate intake (AI) for Se and B12 in adults with data from EFSA's Dietary Reference Value (DRV) tool (EFSA 2017). The average requirement (AR) is the intake of a nutrient that suffices the daily needs of half the people in a healthy population. The use of the adequate intake (AI) is appropriate when there is not enough data to provide an average requirement. An adequate intake is the average nutrient level consumed on a daily basis by a healthy population and that is assumed to be appropriate for the population's needs (EFSA 2017).

Since the ARs for Zn and Fe differ based on gender, we used a mean value between the two. Hence, the AR for Zn is 9.2 mg/day and for Fe 6.5 mg/day. For Se, the AI used is 70 µg/day, and for B12 4 µg/day.

The bioavailability of these nutrients is taken into consideration in the AR and AI. Fe is found in meat as heme iron, while in plant it is in a non-heme form with a lower bioavailability. We assumed that the absorption of heme iron (AB_{hFe}) is around 25% and that approximately 10% if iron in the diet consists of heme iron ($Diet_{hFe}$) and that the absorption of both non-heme and heme iron (ABtotal) is 15% (Fabricius et al. 2021). According to Eq. (1), the percentage of absorbed non-heme iron is 13.9%.

$$AB_{nhFe} = \frac{ABtotal - ABhFe \times DiethFe}{DietnhFe} \tag{1}$$

$$AB_{nhFe} = \frac{0.15 - 0.25 \times 0.1}{0.9} = 0.139$$

Dietary Exposure Assessment and Health Impact

To estimate the chronic exposure to contaminants associated with potential health effects, we calculated the average daily dose (ADD), respectively, the lifetime average daily dose (LADD) as shown in Eqs. (2) and (3):

$$\text{ADD } (\mu g/\text{kg bw/day}) = \frac{Cc \times CONf}{bw} \tag{2}$$

$$\text{LADD } = \frac{ADD \times EF \times ED}{AT}, \tag{3}$$

where C_c = concentration of the contaminant found in food (heavy metals, pesticides, AFB1), CONf = food consumption, bw = bodyweight, EF = exposure frequency (days), ED = exposure duration (years), AT = average time of exposure (days); for carcinogenic risk AT = life expectancy (80 years), while for non-carcinogenic risk AT = EF.

Estimation of the Health Impact

Inorganic Arsenic

The dose–response relationships for all the contaminants, food, and nutrients from this study are presented in Supplementary File S1.

The lifetime cancer risk (LCR) of lung, bladder, and skin cancer for adult European consumers was calculated using Eq. (4), while the annual cancer risk (ACR) was calculated using Eq. (5):

$$\text{LCR} = \text{LADD} \times \text{r} \tag{4}$$

$$\text{ACR} = \frac{LCR}{LE},$$

where r = risk coefficient of developing cancer (Supplementary File S1), and LE = life expectancy of the exposed population.

Lead and Cadmium

In this study, we used the relative risks (RR) and hazard ratios (HR) from meta-analyses to assess the risk of CVD and IHD from Pb and Cd using the following equations:

$$\beta = \frac{\ln \text{RRliterature}}{\text{Dose}} \tag{5}$$

$$\text{RRi} = \exp(\beta \times \text{exposure}_i), \tag{6}$$

where ln RRliterature = logarithm natural of the RR of a specific dose reported in the literature, RRi and $exposure_i$ are the relative risks and exposure to contaminants in the reference scenario and alternative scenario.

Afterward, the potential impact fraction (PIF) was calculated to investigate the impact of each scenario on the burden of disease in adult European consumers using the following Eq. (7):

$$\text{PIF} = \frac{\text{RRalternative scenario} - \text{RRreference scenario}}{\text{RRreference scenario}}, \tag{7}$$

where RRalternative scenario = the RR in the alternative scenario in which we simulated the consumption of legumes only and RRreference scenario = the RR in the reference scenario with unprocessed red meat, processed meat, and legumes consumption.

Based on available data, the risk of CVD due to exposure to Cd is correlated with the concentration of urinary Cd. To assess the risk of CVD-Cd-related cases, we used a toxicokinetic model that describes the relationship between dietary Cd exposure and urinary Cd (U−Cd) (Amzal et al. 2009) (Eq. 8):

$$\mathrm{U-Cd} \; = \times \, \mathrm{d} \, \times \, \mathrm{t} \, \times \frac{\left[1-\exp\left(-\frac{\log(2)\times age}{t}\right)\right]}{\left[1-\exp\left(-\frac{\log(2)}{t}\right)\right]}, \tag{8}$$

where the mean of the product of Fk, an aggregated physiological parameter, and Fu, an elimination factor is 0.005. The Cd biological half-life (t) follows a lognormal distribution with a mean of 11.6 and standard deviation of 3 years. The dietary exposure "d" is expressed in µg/kg bw/day. Using these parameters, we estimated the annual U−Cd assuming that the pharmacokinetic parameters are the same across all countries in this study.

To estimate the annual risk of CVD and IHD due to Pb and Cd exposure, we multiplied the PIF with the annual incidence of the above-mentioned diseases which we retrieved from the Global Burden of Disease (GBD) database (Abbafati et al. 2020).

Aflatoxin B1

AFB1 is carcinogenic to humans and can cause liver cancer (LVC) (IARC 2019). The average LVC potency and risk of LVC from exposure to AFB1 per 100,000 individuals was assessed using the formulas from the Joint FAO/WHO Expert Committee on Food Additives (JECFA) (FAO/WHO 2018) (Supplementary File S1).

The LVC potency for HBV-positive individuals is 0.3 cancer cases per 100,000 persons/year/ng AFB1/kg bw/day and 0.01 cancer cases per 100,000 persons/year/ng AFB1/kg bw/day for HBV-negative individuals (FAO/WHO 2018).

Selenium

Dose–response relationships from the report of the World Cancer Research Fund (WCRF) show an inverse association between Se intake and risk of prostate cancer (WCRF et al. 2018) (Supplementary File S1). The reduced risk of prostate cancer was calculated as mentioned at subsection 2.7.3.

Pesticides

In this study, we assessed the potential risk of chronic acetylcholinesterase inhibition (CAG-NCN), hypertrophy, hyperplasia and neoplasia of C-cells (CAG-TCP), and hypothyroidism (CAG-TCF) (Anastassiadou et al. 2021; EFSA and Dujardin 2021). Dose–response relationships for the risks to develop adverse health effects (cancer/non-cancer) based on the concentration of pesticides residues ingested are in Supplementary File S1.

Unprocessed Red Meat, Processed Meat, and Legumes

For the reduction of the risk of iron deficiency anemia (IDA) due to consumption of unprocessed red meat and the increased risk of CRC, T2D, and IHD from the consumption of processed meat, we used the relative risks (RR) from the World Cancer Research Fund (WCRF) (WCRF 2018) and an UK study with data from 474,996 men and women (Knuppel et al. 2020; Papier et al. 2021) (Supplementary File S1). For legumes, the RR of reducing IHD was taken from a meta-regression based on studies from USA, Japan, and Europe (Afshin et al. 2014) (Supplementary File S1). The potential health effect was calculated as mentioned at subsection 2.7.3.

Estimating the Burden of Disease Using DALYs

DALYs are the sum of the years of life lost due to disability (YLD) and years of life lost due to premature mortality (YLL). One DALY is considered equal to one healthy year of life lost.

The burden of disease was calculated by retrieving data from the GBD (Abbafati et al. 2020) related to incidence of the disease (i.e., IHD) and the associated YLLs, YLDs, and DALYs at country-specific level (Abbafati et al. 2020). In order to align with established global health envelopes, we calculated conversion factors to transform our illnesses incidence estimates into estimates of YLL, YLD, and DALYs. Our aim was to ensure consistency with the World Health Organization/Global Health Estimates (WHO 2019). Therefore, the burden of disease was estimated as follows:

$$\mathrm{YLL}_{\text{risk factor}} = \mathrm{Incidence}_{\text{illness}} \times \frac{YLLGBD}{IncidenceGBD} \tag{9}$$

$$\mathrm{YLD}_{\text{risk factor}} = \mathrm{Incidence}_{\text{illness}} \times \frac{YLDGBD}{Incidence, GBD} \tag{10}$$

$$\mathrm{DALY} = \mathrm{YLL} + \mathrm{YLD}, \tag{11}$$

where risk factor = the contaminants and foods from this study (i.e., i-As, AFB1, processed meat, etc.), $\mathrm{Incidence}_{\text{illness}}$ = the incidence of the illnesses (i.e., lung cancer, liver cancer, etc.) from this study, YLL GBD, and YLD GBD are the YLL and YLD rates for country-specific of the all-cause illnesses from GBD (Abbafati et al. 2020), and

Incidence GBD are the country-specific rates of illnesses from the GBD (Abbafati et al. 2020).

Due to lack of dose–response relationships for Fe, Zn, and B12 intake, we could not quantify the health impact.

The health impact change between the reference and alternative scenario was calculated based on the difference between DALYs as shown in Eq. (12):

$$\Delta DALY_{AS} = DALY_{AS} - -DALY_{BS}. \tag{12}$$

If $\Delta DALY_{AS} < 0$, it indicates a health gain resulting from averting DALYs. On the other hand, if $\Delta DALY_{AS} > 0$, it signifies a health loss due to the increase in DALYs caused by the dietary pattern shift. The statistical analyses were realized using Microsoft Excel 21 (Microsoft, Redmond, Washington) and SPSS Statistics 26 (IBM Software Group, Chicago, IL).

For all the calculations, we performed Monte Carlo simulations using the Oracle Crystal Ball Software 11.1.3 (Oracle USA, Inc., Redwood City, CA). We ran 100,000 iterations to propagate variability and 10,000 iterations to propagate uncertainty. The values are reported as the mean of the variability and the median of the uncertainty dimension with 95% uncertainty intervals (UI) regarding the health effects such as potential incidence of illnesses, YLLs, YLDs, and DALYs.

Results

To assess the health impact and burden of disease for both the reference scenario (RS) and alternative scenario (AS), we used the optimistic (OS) and pessimistic (PS) exposure approach from the European Food Safety Authority (EFSA). This allows us to present both a less conservative estimate, reflecting a more favorable outlook (OS), and a more conservative estimate (PS), accounting for a higher level of caution. By considering these two scenarios, we aim to provide a comprehensive understanding of the health implications associated with different levels of risk and burden of disease.

Burden of Disease for European Adult Consumers due to Dietary Exposure to i-As, Pb, Cd, and AFB1 from the Consumption of Unprocessed Red Meat, Processed Meat, and Legumes

We assessed the risk of six illnesses due to chronic exposure to i-As, Pb, Cd, and AFB1 in an optimistic/pessimistic reference scenario (RS OS/PS) with consumption of unprocessed red meat, processed meat, and legumes, and a simulated alternative scenario (AS OS/PS), where the consumption of meat was replaced with the consumption of legumes. The estimated health risk, years lived with disability (YLDs), years of life lost (YLLs), and DALYs for each country are outlined in Supplementary File S2. Additional figures are presented in Supplementary File S3.

The potential incidence of illnesses due to chronic exposure to chemical contaminants in Europe is presented in Fig. 1a. The annual risk of lung cancer (LC) due to chronic exposure to i-As in the RS was between 20.3 and 94.5, while in the AS the risk was higher ranging from 56.7 to 192.4 additional cases. Similar values were estimated for the risk of skin cancer (SC) with values as low as 30.4 cases in the RS and as high as 288.5 cases in the AS. The incidence of bladder cancer (BC) cases due to exposure to i-As was lower between 8.1 (RS OS) and 76.9 (AS PS).

The risk of cardiovascular disease (CVD) due to exposure to Cd was lower in the AS between 40,017 and 42,148, while in the RS the risk of CVD was higher at 39,595–77,018 cases. This is related to the slightly higher occurrence level of Cd in the pessimistic scenario (PS) for processed and unprocessed red meat compared with legumes.

The highest health risk in both scenarios comes from the exposure to Pb. The risk of IHD was estimated between 34,385 (RS OS) and 60,214 (RS PS) cases, while in the AS the risk was two times higher with values reaching up to 62,848 IHD cases. The estimated incidence of CVD-Pb-related cases varied from 64,427 (RS OS) to 117,474 (AS PS) cases, indicating that even if plant-based diets are recommended for the prevention of CVD, if not properly regulated and controlled, the increased exposure to Pb could have the exact opposite effect. Among the six contaminants from this study, Pb has the highest contribution to the burden of disease in Europe.

A lower health risk comes from the exposure to AFB1, where the estimated liver cancer risk (LVC) ranged from 0.5 (RS OS) to 25.9 cases (AS PS).

For the burden of LC, BC, SC, IHD, CVD, and LVC due to exposure i-As, Pb, Cd, and AFB1 in Europe, we calculated the DALYs that would be gained in the RS and AS (Fig. 1b).

Exposure to i-As can lead to the loss of 427.1 (RS OS) – 4068 (AS PS) healthy years of life for adult consumers due to the risk of LC, SC, and BC. LC alone can lead to the loss of 3502 years of life (AS PS). LC is the leading cause of cancer death in the world with a survival rate of only 18.6% (https://www.lung.org/lung-health-diseases/lung-disease-lookup/lung-cancer/basics), while for BC and SC the survival rates are 77% (https://www.cancer.net/cancer-types/bladder-cancer) and 99% when localized (https://www.cancer.org/cancer/types/melanoma-skin-cancer/detection-diagnosis-staging/survival-rates-for-melanoma-skin-cancer-by-stage.html).

The burden of IHD and CVD due to exposure to Pb lead to the gain of 188,986 (RS OS) – 345,925 (AS PS) DALYs, respectively, 299,496 (RS OS) – 547,376 (AS PS) DALYs,

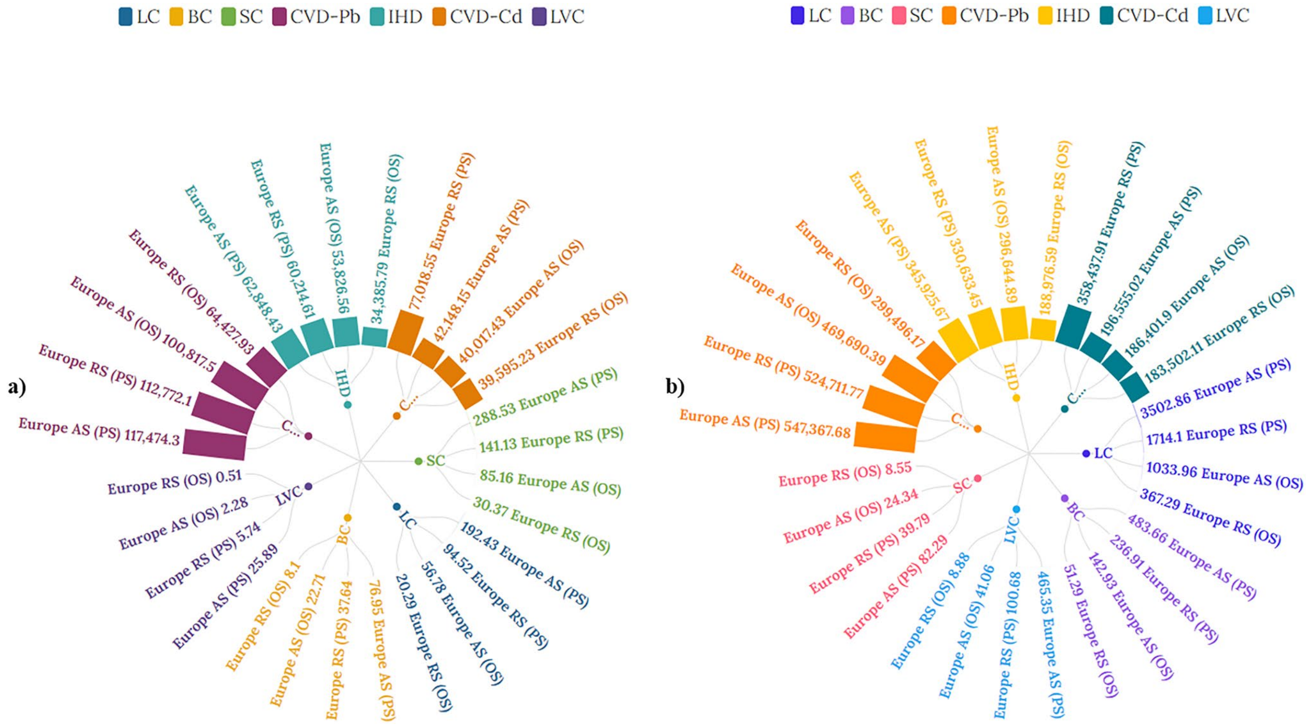


Fig. 1 **a** The estimated incidence of illnesses for adult European consumers due to chronic dietary exposure to i-AS, Pb, Cd, and AFB1; *RS OS/PS* reference optimistic/pessimistic scenarios; *AS OS/PS* alternative optimistic/pessimistic scenarios; *LC* lung cancer; *SC* skin cancer; *BC* bladder cancer; *LVC* liver cancer; *CVD* cardiovascular disease; *IHD* ischemic heart disease; **b** The estimated burden of disease for adult European consumers expressed in DALYs due to chronic exposure to i-AS, Pb, Cd, and AFB1

which translates to the loss of half a million years of healthy life.

The CVD-related burden from exposure to Cd was quantified between 183,502 (RS OS) and 186,401 (AS PS) DALYs per year in Europe. As a comparison, in China, the burden of coronary heart disease (CHD) from dietary exposure to Cd is estimated at 3.26 million DALYs or 281.59 DALYs per 100,000 individuals (Liu et al. 2022). In our study, the average rate of burden is estimated at 73.1–150.9 DALYs/100,000 individuals.

Although the risk of LVC was low it can still lead to a burden of 8.8 – 465.3 DALYs per year indicating that even at low exposure levels the associated burden is considerable. This is due to the severity of LVC and the fact that when localized the survival rate is only 31% (https://www.cancer.org/cancer/types/liver-cancer/detection-diagnosis-staging/survival-rates). While this statistic emphasizes the serious nature of LVC and underscores the need for preventive measures and early detection to improve outcomes and reduce the burden on affected individuals and healthcare systems, it also highlights the importance of regulations of mycotoxins in legumes which would significantly reduce the exposure, respectively, the risk of LVC. In Europe, the incidence of LVC in 2019 was reported to be 65,395 cases with 60,219 LVC-related deaths indicating a mortality-to-incidence ratio of 92% (Abbafati et al. 2020).

Regarding the burden of disease due to exposure to pesticides, the risk is negligible and was not illustrated here but can be seen for each country in Supplementary File S2. In the RS, the risk was low with an estimated 0.09 potential cases of neurological disorders (0.015 DALYs), 0.07 potential hypothyroidism cases (0.0002 DALYs), and 0.02 potential health risk cases of hypertrophy, hyperplasia, and neoplasia of C-cells (0.0006 DALYs). In the AS, the health risk was higher but still negligible with 0.43 potential cases of neurological disorders (0.07 DALYs), 0.34 cases of hypothyroidism (0.01 DALYs), and 0.08 potential cases of hypertrophy, hyperplasia, and neoplasia of C-cells (0.003 DALYs) at the European level.

Burden of Disease for European Adult Consumers due to the Consumption of Unprocessed Red Meat, Processed Meat, and Legumes

Using data from meta-analyses and cohort studies, we estimated the health risks and benefits for adult European consumers based on the consumption of unprocessed red meat, processed meat, and legumes in the RS and AS. The estimated health risk, benefits, YLDs, YLLs, and DALYs for each country are outlined in Supplementary File S4.

Figure 2a provides an overview of the extra/prevented incidence of illnesses associated with the consumption of unprocessed red meat, processed meat, and legumes at the European level. In the RS across Europe, the consumption of processed meat is estimated to contribute to 444,978 cases of T2D, 165,630 cases of IHD, and 24,049 cases of CRC.

However, in the AS, the removal of processed meat consumption also removed the risk of T2D, IHD, and CRC. Furthermore, the consumption of legumes is associated with a reduced risk of IHD, potentially preventing 243,271 cases of IHD at the European level.

Consumption of unprocessed red meat is estimated to potentially prevent 163,841 iron deficiency anemia (IDA) cases per year in Europe. Switching to a plant-based diet (AS) would remove this benefit.

Based on the intake of Se, in the RS the reduced risk of PC was 104,961 cases, whereas in the AS, the reduced risk of PC was at 29,771 cases indicating a decrease in the health benefits due to a lower Se intake.

For the burden of consuming unprocessed red meat, processed meat, and legumes, we quantified the DALYs that would be gained/averted in the RS and AS (Fig. 2b).

The burden that would be gained from the risk of CRC was 201,464 DALYs, which translates to the loss of to 201,464 healthy years of life in Europe. The highest burden comes from T2D with 1,175,774 DALYs and from the risk of IHD with up to 939,882 DALYs. Consumption of unprocessed red meat would avert 3276 DALYs by reducing the risk of IDA. Meanwhile, switching to the AS would avert 221,377 DALYs due to the reduced risk of IHD.

The averted burden by preventing the risk of PC was 500,507 DALYs in the RS and 143,416 DALYs in the AS, indicating a higher benefit in a mixed diet with both meat and legumes.

The potential health risks related to the consumption of processed meat are likely heavily influenced by the specific processing methods and the use of nitrites. However, due to insufficient data, we were unable to thoroughly examine these factors. Consequently, our calculations pertain to the projected risks and benefits of consuming processed meat.

Overall, the incidence of illnesses in the RS due to chronic exposure to chemical contaminants was between 138,464 and 250,284 (mainly IHD and CVD-related cases due to exposure to Pb and Cd) with 672,410–1,215,875 DALYs, while in the AS the health risk varied between 196,959 and 220,923 cases (mainly CVD-related cases due to exposure to Pb and Cd) with a burden of 964,132 and 1,084,229 DALYs. For the burden associated with consumption of unprocessed red meat, processed meat, and legumes in the RS, we estimated 336,084 extra incidences of illnesses (mainly due to IHD and T2D from processed meat) with a burden of 1,813,338 DALYs, while in the AS up to 273,043 IHD cases could be prevented (due to the removal of processed meat from the diet and the increased intake of legumes) with 364,973 averted DALYs. Based on Eq. (12), in the optimistic

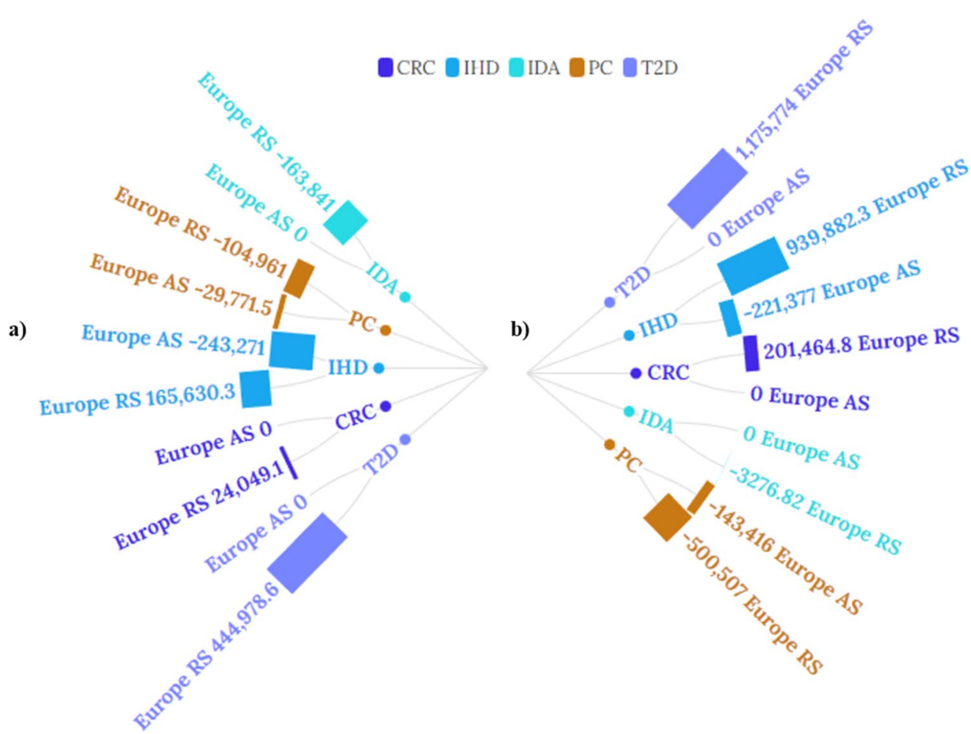


Fig. 2 **a** The estimated incidence of extra/prevented illnesses for adult European consumers based on the consumption of unprocessed red meat, processed meat, and legumes; *RS* reference scenarios; *AS* alternative scenarios; **b** The estimated burden of disease expressed in DALYs for adult European consumers based on the consumption of unprocessed red meat, processed meat, and legumes

scenario (OS) there is a health loss ($\Delta DALY_{AS} > 0$) due to the exposure to contaminants in the AS, while in the pessimistic scenario (PS) there is a health gain ($\Delta DALY_{AS} < 0$). This is particularly due to the slightly higher upper bound occurrence levels of Cd in meat compared with legumes, indicating the significant contribution of each contaminant in the overall health risk based on different occurrence levels. For the consumption of unprocessed red meat, processed meat, legumes (RS), and legumes only (AS), $\Delta DALY_{AS} < 0$ indicating a health gain due to the shift in dietary patterns.

Comparing these scenarios, the burden of disease (DALYs) in AS (vegan diet) is higher within the given ranges than in the RS (omnivore diet). This indicates that, according to our findings, the burden of disease in the AS due to chronic exposure to chemical contaminants might be relatively higher than in RS. It is important to note that for both scenarios the estimated burden does not take into account additional factors such as susceptibility among populations and countries, access to healthcare, and other environmental and lifestyle aspects.

Estimating Nutrient Adequacy for Adult European Consumers Based on the Consumption Of Unprocessed Red Meat, Processed Meat, and Legumes

The nutritional intake expressed in percentage of adequate intake (AI) and average requirement (AR) for vitamin B12, Iron, Zinc, and Selenium for all 25 countries in the RS and AS can be seen in Fig. 3.

Overall, an average of 24.6% of the adequate intake (AI) of Se is gained in the RS, while in the AS only 6.18% of the AI for adults is attained. Regarding Zn, 56.9% of the average requirement (AR) is provided by meat and legumes in the RS, while in the AS legumes consumption leads to only 16.3% of the AR. The RS secures 56% of the recommended AI of vitamin B12 and 10.3% of the AR of Fe, while in the AS no source of vitamin B12 is present in the AS and only 6.3% of the AR of Fe is gained.

Uncertainty and Limitations

Under/over-reported food consumption data together with the proportion of left-censored data might have led to the under/overestimation of the exposure, consequently the

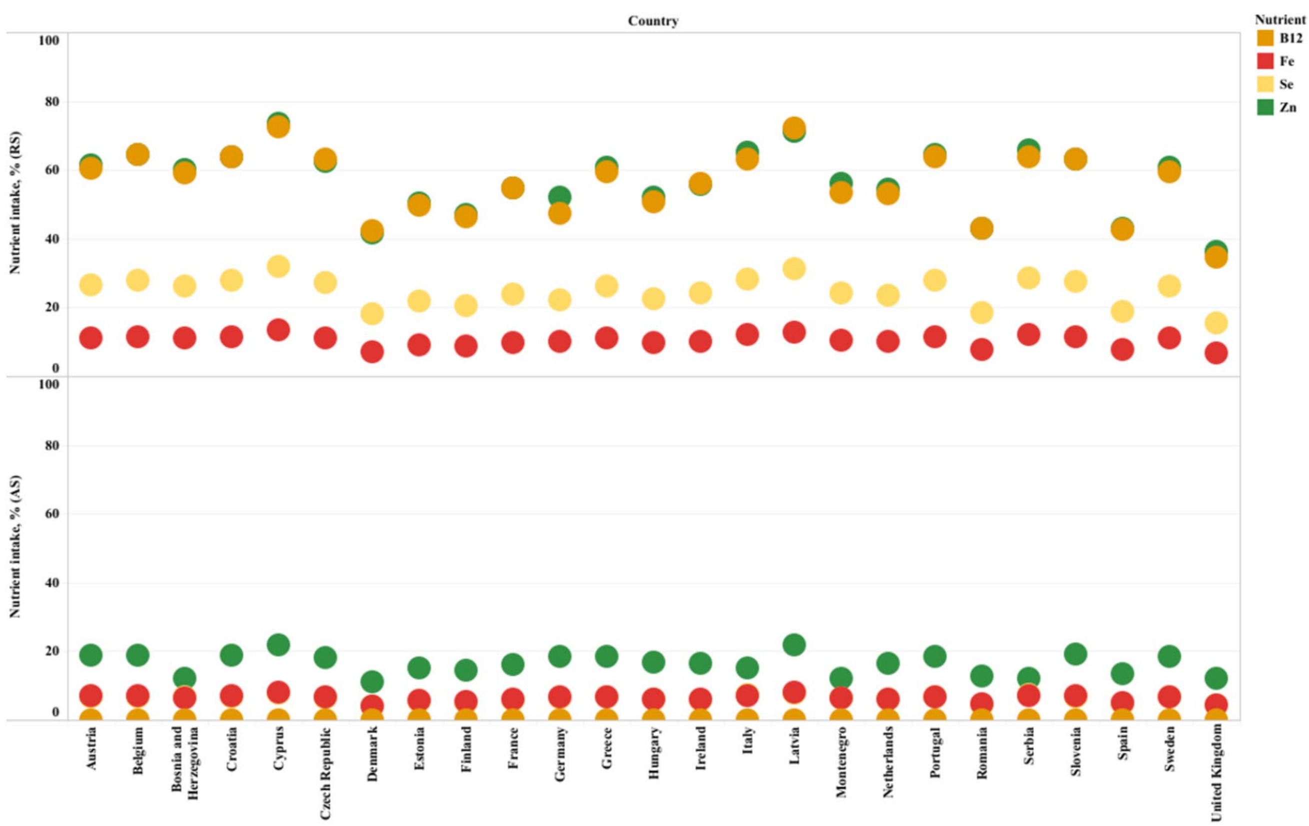


Fig. 3 Percentage of nutrient intake for vitamin B12, Iron, Selenium, and Zinc for adult European consumers in the reference scenario (RS) and alternative scenarios (AS)

health risks/benefits and associated burden of disease. Using the available contamination data may also lead to potential overestimation (risk from i-As) or underestimation (risk from AFB1) of the combined burden of disease. However, the consumption and contamination data along with dose–response relationships are from official reports from EFSA (EFSA 2012a; EFSA 2012b; Arcella et al. 2021; Schrenk et al. 2020) and meta-analyses with large cohorts and international health institutions, therefore imposing the same uncertainties in the health impact evaluations and risk assessments at the European level.

By relying on risk coefficients from other studies, we might have overlooked the specific characteristics of the diverse populations from the 25 European countries included in this study. These populations could have different baseline risks, genetic backgrounds, or exposure patterns. This assumption could lead to an overestimation of the actual risks and benefits of the dietary habits from this study.

It is unlikely that an individual will be diagnosed with several different types of cancer and/or cardiovascular diseases in the same year. This clearly led to an overestimation in the final number of illnesses and DALYs in each scenario. While uncertainties were quantified using probabilistic analyses, our findings should be carefully considered as estimates of risk and benefits with bounds of plausible effects.

The removal of unprocessed red meat/processed meat might be in common practice compensated by a higher consumption of dairy products, cereals, etc. While in vegan diets the consumption of legumes remains relatively high, vegetarian diets might involve a lower legume consumption than in our model, therefore a potentially lower exposure to the contaminants from this study.

Finally, our estimations are influenced by publication bias. Reliance on published studies may be subject to publication bias, where studies with positive or significant findings (i.e., reduced risk of ischemic heart disease from legumes consumption) are more likely to be published than those with null or negative results. This bias can lead to an overestimation of the true effect size, in our case the health risk/benefit associated with dietary patterns.

Discussion

This study highlights that shifting diets may also shift the exposure to selected chemical contaminants and potential nutritional inadequacies. DALYs were used to effectively convey to the lay public and policy makers the health burden associated with contaminants in foods and differences between omnivore and simulated vegan/vegetarian diets.

Beneficial and adverse health effects can arise based on the type of diet. With the exception of Cd being regulated in vegetables and Pb in pulses, contaminants such as i-As and aflatoxins have no proper regulations in legumes such as soybeans, chickpeas, and pea, the main common ingredients of plant-based meat alternatives which are often found in vegan/vegetarian diets.

While research related to the dietary burden of disease is ongoing, there is a gap as to which are the risks and benefits, respectively, the human health impact of each diet. Cohort studies indicate that increased blood lead levels are associated with an increased IHD and CVD mortality (Lanphear et al. 2018). Worldwide, based on the blood lead levels, up to 256,000 and 185,000 excess deaths were attributed to CVD and IHD, indicating that low levels of lead exposure, usually ignored by clinicians, represents a major cardiovascular risk factor (Lanphear et al. 2018). In our study, Pb and Cd lead to the highest burden indicating that the shift in diets can lead to an increased exposure to cardiovascular risk factors.

The highest reported burden of disease from dietary exposure to Pb comes from North Africa and Middle East, where a burden of 414.2 DALYs/100,000 individuals was attributed to Pb-CVD-related cases (Shahbandi et al. 2022). To provide a comparison, in Europe the annual burden from CVD and IHD-Pb-related cases would be lower between 41.1 and 238.2, respectively, 79.9–155.6 DALYs/100,000 individuals.

The potential burden from exposure to AFB1 was lower than other contaminants but still relevant considering the low survival rate of LVC. A higher risk of LVC from AFB1 in a vegan diet was previously reported in Italy in a model, where meat was replaced with soy-based meat analogs (Mihalache et al. 2022) indicating that the exposure model is heavily dependent on the available contamination data. Assuming the presence of aflatoxins in our food and considering the current lack of specific regulations adds a layer of complexity when considering the potential health impact of aflatoxin exposure. Therefore, continuous monitoring of mycotoxins such as AFB1 in legumes may require higher attention in order to keep the exposure as low as reasonably achievable.

According to O'Hearn et al. (2023), in 2018 a total of 14,100,000 global cases of T2D were attributed to suboptimal intake of 11 dietary factors. Among these factors, excessive consumption of processed meat stood out as a significant contributor. The largest burdens of T2D were associated with inadequate whole-grain intake (26.1%), followed by excessive intake of refined rice and wheat (24.6%), and excess consumption of processed meat (20.3%). Furthermore, in central and eastern Europe, as well as central Asia, an estimated 927,312 cases of T2D were identified. Out of these cases, 55.7% were found to be attributable to high consumption of processed meats (O’Hearn et al. 2023).

We present comparable results to the Global Burden of Disease (Abbafati et al. 2020) database for the burden of processed meat consumption with 939,882.3 DALYs attributable to IHD (2.7% of the total IHD burden in

Europe), 1,175,774 DALYs for T2D (14.9% of the total T2D burden in Europe), and 447,407 DALYs for CRC (7.7% of the total burden of CRC in Europe).

From a nutritional point of view, shifting diets limits the benefits of Fe and Se and also lowers the intakes of Zn and vitamin B12. Adult vegans have significantly lower intakes of iodine, calcium, vitamin D, selenium, and vitamin B12 than vegetarians and omnivores (Fallon and Dillon 2020). By removing red meat from the diet vegetarians and vegans have an increased risk to being anemic compared with meat consumers (Tong et al. 2019). It should be noted that in this study we presented only a set of essential nutrients and that the risk of nutrient inadequacies in the alternative scenario might even be higher.

Although it is unlikely for a full replacement scenario to take place due to differences in eating behaviors with some citizens being low-legume eaters and others are high eater, this present study has showed the burden of disease of consuming unprocessed red meat, processed meat, and legumes (omnivores) and a simulation of legumes scenario only (vegans/vegetarians).

The increasing shift toward plant-based milk and plant-based meat make up the majority of the plant-based foods consumed by flexitarians in Europe (Smart Protein Project 2021). The current risk related to processed meat consumption will be replaced by a new increasing risk derived from contaminants in legume-based diets.

WHO started the first initiative to estimate the global burden of disease caused by chemical contaminants in food such as dioxins, aflatoxins, cassava cyanide (Havelaar et al. 2015), and four heavy metals: arsenic, lead, cadmium, and methylmercury and encourages efforts to produce region and national specific estimates for the burden of foodborne illnesses (Gibb et al. 2019). Therefore, this study contributes as a further component to the WHO initiative of estimating the global burden of foodborne diseases by showing the risks and benefits in an omnivorous and vegetarian/vegan diet considering the chronic exposure to i-As, Cd, Pb, and AFB1.

By quantifying the health impact based on dietary trends, this study provides data basis for national and European public health policy such as potential and unexpected risks that may arise in shifting diets and setting standard limits for selected contaminants in legumes as it is the case for other commodities such as wheat and maize.

Although toxicology-based risk assessments are commonly used to inform food safety actions, they do not encompass the overall disease burden in populations. When implementing policy decisions, the necessary trade-offs between shifting diets must be taken into consideration, thus increasing the importance of studies such as the present one. The results of the present study should be used to inform public health policies in the area of food safety and implement strategies to limit the burden of disease based on the type of diet and exposure to chemical contaminants.

While it is important to fully acknowledge the relevance of adhering to alternative protein sources to ensure sustainable dietary patterns within the United Nations Sustainable Goals (UN SDGs) policy framework, for a genuine shift toward sustainable as well as healthier diets, policymakers should implement regulatory frameworks that take into consideration new products that are on the horizon coupled with new dietary trends.

Conclusions

The main health benefits from consumption of unprocessed red meat, processed meat, and legumes in conjunction with the potential risks from hazardous chemicals present in these foods have not been previously considered. The present study can be regarded as a first attempt to evaluate the human health impact in shifting diets for adult European consumers.

A shift to a plant-based diet essentially eliminates a health risk factor such as processed meat; nevertheless, if naturally occurring chemical contaminants are not effectively monitored and controlled in legumes and legume-based products, increased and unanticipated risks may well occur. Micronutrient intakes were lower in the AS, thus reducing the health benefits associated with the intake of selenium and iron such as a lower risk of prostate cancer and iron deficiency anemia. These are extremely important factors that need to be taken into account when risk-benefit assessments of diet shifts are considered from a human health perspective.

A balanced diet with a variety of meal types and avoiding excessive consumption of any particular food is essential to maintain dietary exposures to chemical contaminants at levels below where they will pose additional health risks.

Greater importance should be given to actual food consumption trends and associated with updated natural toxins legislation and risk assessments in view of the ubiquitous occurrence of heavy metals and mycotoxins, also in light of climate change, and the growing tendency toward plant-based diets.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12403-024-00634-8.

Author Contributions OAM: conceptualization, methodology, software, formal analysis, investigation, writing—original draft, writing—review & editing, and visualization; CE: investigation, and writing—review & editing; CD: conceptualization, methodology, resources, writing—review & editing, project administration, and supervision.

Funding Open access funding provided by Università degli Studi di Parma within the CRUI-CARE Agreement. OAM was supported by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie Grant Agreement No. 101110615 (PRISMA project). Activities have been partially funded under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3—Call for tender No. 341 of 15/03/2022 of Italian Ministry of University and Research funded by the European Union–NextGenerationEU. Award Number: Project code PE0000003, Concession Decree No. 1550 of 11/10/2022 adopted by the Italian Ministry of University and Research, CUP 93C22000890001, Project title "Research and innovation network on food and nutrition Sustainability, Safety and Security–Working ON Foods" (ONFOODS). This work has been carried out in the frame of the ALIFAR project, funded by the Italian Ministry of University through the program "Dipartimenti di Eccellenza 2023-2027".

Data Availability The risk coefficients used and datasets generated and/or analyzed during the current study are available in the Zenodo repository (Supplementary files S1, S2, S3, and S4). https://zenodo.org/records/10839762.

Declarations

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.

Ethical Approval This study does not require ethical approval.

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