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Substituting red meat with insects in burgers: Estimating the public health impact using risk-benefit assessment

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ABSTRACT

In Western societies, reducing red meat consumption gained prominence due to health, environmental, and animal welfare considerations. We estimated the public health impact of substituting beef with house cricket (*Acheta domesticus*) in European diets (Denmark, France, and Greece) using the risk-benefit assessment (RBA) methodology, building upon the EFSA-funded NovRBA project. The overall health impact of substituting beef patties with insect powder-containing patties was found to be impacted by the amount of cricket powder incorporated in the patties. While using high amounts of cricket powder in meat substitutes may be safe, it does not inherently offer a healthier dietary option compared to beef. Adjustment of cricket powder levels is needed to yield a positive overall health impact. The main driver of the outcome is sodium, naturally present in substantial amounts in crickets. Moreover, the way that cricket powder is hydrated before being used for the production of patties (ratio of powder to water), influences the results. Our study highlighted that any consideration for dietary substitution should be multidimensional, considering nutritional, microbiological and toxicological aspects, and that the design of new food products in the framework of dietary shifts should consider both health risks and benefits associated with the food.

1. Introduction

In Western societies, the reduction of red meat consumption, and especially of its processed form, has been identified among priority actions to enhance public health (De Backer and De Henauw, 2019; FVM, 2021; García et al., 2023; James et al., 2022). This consideration is driven by a growing body of evidence linking the consumption of red meat, especially its processed forms, to an increased risk of chronic diseases including colorectal cancer, diabetes type 2, and cardiovascular diseases (González et al., 2020). Environmental considerations (e.g., carbon footprint of red meat production) as well as ethical concerns related to animal welfare further contribute to the discussion (Boehm et al., 2021; Bonnet et al., 2020; González et al., 2020). Nevertheless, red meat is a valuable source of (high-quality) protein, containing a well-balanced array of essential amino acids, readily absorbed by the human body, and essential micronutrients such as cyanocobalamin (vitamin B12), iron, and zinc (Cocking et al., 2020; De Smet and Vossen, 2016).

The dietary reduction of red meat will likely result in an increased consumption of alternative protein sources, such as edible insects (Banach et al., 2022; Van der Weele et al., 2019). In the European Union (EU), insects and products thereof are considered as novel foods according to Regulation (EU) 2283/2015, and their safety must be evaluated before placing them in the EU market (Precup et al., 2022; Ververis et al., 2020). Consumption of insects as food is not common in Western societies (Sogari et al., 2023), with a limited acceptance due to cultural aspects, food neophobia and product characteristics (Boehm et al., 2021; Kröger et al., 2022). A strategy to enhance the acceptance of insect-derived foods is incorporating them in hybrid food products, in which a portion of the meat is replaced by powdered insects (Grasso and Goksen, 2022; Grasso et al., 2022; Talens et al., 2022).

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Abbreviations

DALYs - Disability-Adjusted Life Years
CHD - Coronary Heart Disease
CVD - Cardiovascular Disease
DANSDA - Danish National Survey of Diet and Physical Activity
EFSA - European Food Safety Authority
EU - European Union
GBD - Global Burden of Disease
HFA-DB - European Health for All database
IHME - Institute for Health Metrics and Evaluation
INCA3 survey - Third French Individual and National Food Consumption Survey
PIF - Potential Impact Fraction
PUFA - Polyunsaturated Fatty Acids
RBA - Risk-Benefit Assessment
ROBIS - A Risk of Bias Assessment Tool for Systematic Reviews
WHO - World Health Organization

Several among the studied edible insect species have promising nutrient profiles in terms of protein and micronutrients, especially minerals (Nowakowski et al., 2022) but their use as a red meat substitute in diet has not yet been adequately investigated. Some studies compare mainly the nutrient profiles of meat and insects (Orkusz, 2021; Payne et al., 2016), but such comparisons are considered to provide preliminary indications because aspects such as the bioavailability of nutrients from insects (Ojha et al., 2021), or the link between entomophagy and health has not been adequately investigated and established (Rivero-Pino et al., 2023).

The potential of edible insects as novel dietary sources, and as red meat replacers, should be based not only on a comparison of their nutrient profiles, but also on microbiological and toxicological aspects. Risk-Benefit assessment (RBA) is a decision-support tool that allows for a simultaneous consideration of nutritional, microbiological, and toxicological aspects under a single methodological framework (Boué et al., 2015, 2022; EFSA Scientific Committee, 2010; Nauta et al., 2018). The RBA has been previously used as a tool to evaluate e.g., dietary substitutions of sugar-sweetened beverages by beverages containing intense sweeteners (Husøy et al., 2008), sodium chloride by potassium chloride (Steffensen et al., 2018), and red and processed meat by fish (Thomsen et al., 2018, 2019).

The aim of this study was to perform a quantitative RBA to evaluate the overall health impact associated with substitution of beef with an edible insect species, the house cricket (*Acheta domesticus*), a novel food in the Western world, considering toxicological and microbiological risks, as well as nutritional safety and benefit aspects. The assessment relied on the dietary patterns of three countries covering different regions in Europe: Denmark, France, and Greece and the work was based on the methodological aspects investigated in the framework of the EFSA-supported NovRBA project (Novel foods as red meat replacers - an insight using Risk-Benefit Assessment methods) (Naska et al., 2022).

2. Material and methods

2.1. RBA methodological framework

The RBA followed the stepwise methodological approach illustrated in Fig. 1, adapted from (Assunção et al., 2019; Boué et al., 2015; EFSA Scientific Committee, 2010).

2.2. Definition of RBA question

The RBA question was formulated based on previously described

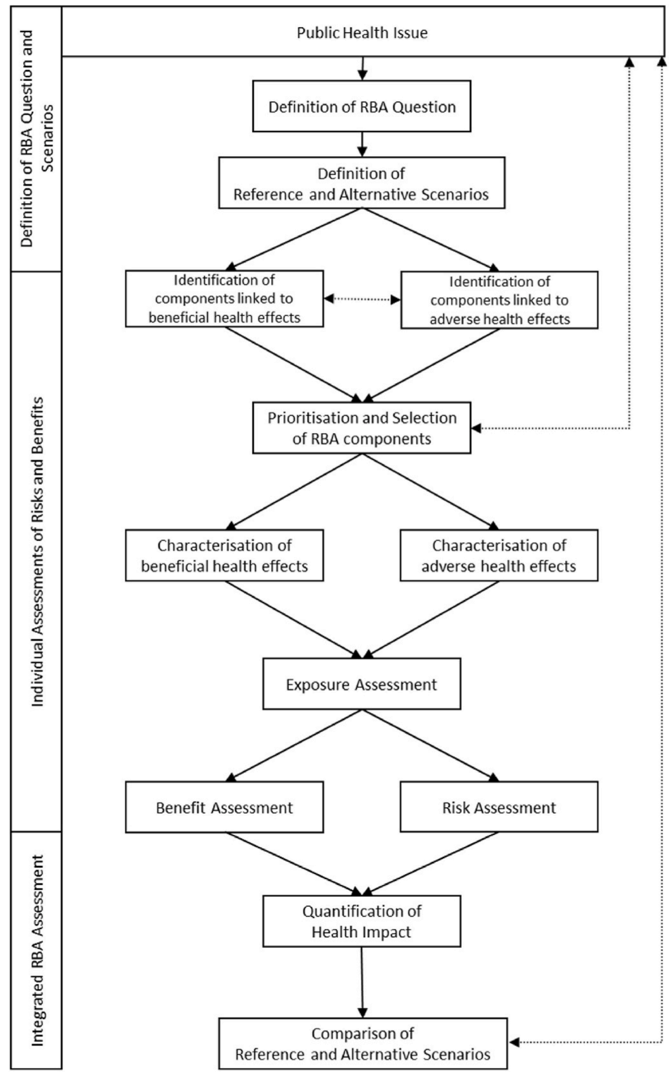

Fig. 1. The implemented RBA stepwise methodological approach (modified from (Assunção et al., 2019; Boué et al., 2015; EFSA Scientific Committee, 2010).

principles (EFSA Scientific Committee, 2010; Nauta et al., 2018). The main elements considered to define the RBA question were the definition of substitution and reference food commodities, the respective food recipes (Fig. 2), the definition of the reference and substitution scenarios (theoretical), as well as the target population.

2.2.1. Definition of substitution and reference food commodities

The insect species *A. domesticus* was selected as per the process described by (Naska et al., 2022). In brief, the market (EU) potential of an insect species, as well as the availability of data on composition and related manufacturing processes primarily shaped the selection of the species to be investigated. The powdered form of the insect was chosen, as available literature on consumers' perceptions regarding edible insects indicates that in the western societies insects may be more acceptable when not visible (e.g., as parts of other foodstuffs, in the form of powder). This is also supported by the recent literature review of (van Huis and Rumpold, 2023). Regarding red meat, beef was selected as it is broadly consumed in European countries by all age groups and because of the negative environmental impacts of cattle farming (Eshel et al., 2014; Poore and Nemecek, 2018; Saget et al., 2021). We subsequently selected to use minced beef in the form of burger patties, to allow for the use of cricket powder in the preparation of a product with similar

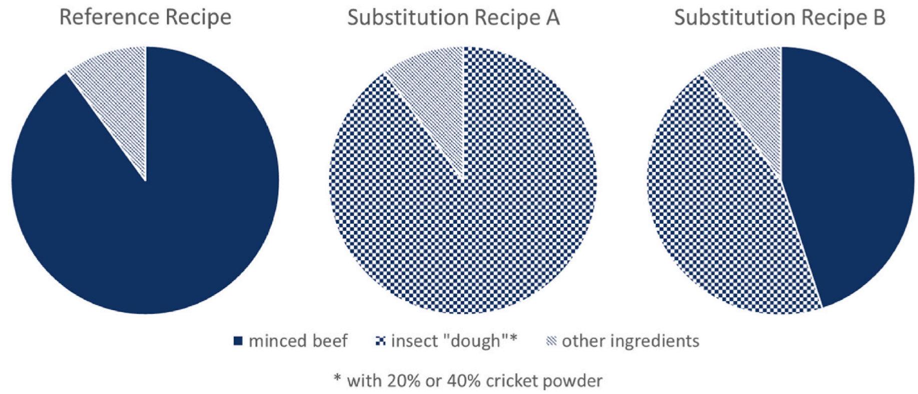

Fig. 2. The recipes under investigation.

appearance.

2.2.2. Definition of the reference and substitution scenarios

To allow for a realistic quantitative comparative approach, the following theoretical scenarios were implemented for the burger patties, assuming that 10% of the ingredients (other ingredients such as herbs, spices, and vegetables, which are common among the different scenarios) in the patties were the same for all the scenarios, to capture variability in the different recipe scenarios (both industrially-prepared and home-prepared patties) (Fig. 2).

- Reference scenario: 90% minced beef and 10% other ingredients
- Substitution scenario A: 90% cricket "dough" and 10% other ingredients
- Substitution scenario B: 45% minced beef, 45% cricket "dough" and 10% other ingredients.

Regarding the preparation of the "cricket dough", our study investigated two distinct possibilities concerning the composition of the dough. In the first one, the hydrated powder comprised 20% cricket powder and 80% water, while in the second one, it consisted of 40% cricket powder and 60% water. The final inclusion levels of cricket powder in the patties were, in each scenario, close or within the maximum permitted levels currently authorised in the European Union [Commission Implementing Regulation (EU) 2017/2470], previously assessed by the (EFSA NDA Panel et al., 2021), i.e. up to 16% and 50% of cricket powder in meat preparations and meat analogues, respectively.

Hence, including the two different compositions of "cricket dough" in substitution scenarios A and B resulted in the following four substitution scenarios.

- Reference scenario, i.e., consumption of patties containing only minced beef.
- Substitution scenario (A1), i.e., the minced beef in the patties is completely substituted by cricket "dough" that comprises 20% cricket powder and 80% water.
- Substitution scenario (B1), i.e., the minced beef in the patties is partially (50%) substituted by cricket "dough" that comprises 20% cricket powder and 80% water.
- Substitution scenario (A2), i.e., the minced beef in the patties is completely substituted by cricket "dough" that comprises 40% cricket powder and 60% water.
- Substitution scenario (B2), i.e., the minced beef in the patties is partially (50%) substituted by cricket "dough" that comprises 40% cricket powder and 60% water.

Considering the above scenarios, the concentration of the main ingredients is presented in Table 1.

Table 1
Concentration of patty ingredients for each scenario.

Ingredients (%)	Scenario				
	Reference	A1[a]	B1[a]	A2[b]	B2[b]
other ingredients	10	10	10	10	10
minced beef	90	0	45	0	45
cricket powder	0	18	9	36	18
water (from the "dough")	0	72	36	54	27

- Reference scenario: 90% minced beef and 10% other ingredients.
- Substitution scenario A: 90% cricket "dough" and 10% other ingredients.
- Substitution scenario B: 45% minced beef, 45% cricket "dough" and 10% other ingredients.

[a] "Dough" cricket powder-to-water ratio = 20:80.
[b] "Dough" cricket powder-to-water ratio = 40:60.

2.2.3. Target population

The general adult population was selected on the basis of research indicating that adults (and young adults in particular) may be more willing to eat insects as food (Naska et al., 2022). The decision to select the general adult population was to ensure the availability of individual food consumption data for this population subgroup in all three countries under investigation.

Considering the above-described elements, the RBA question was formed as follows:

> "What would be the net health impact of partially or totally substituting the beef in burger patties with cricket powder in the adult populations of Denmark, France and Greece?"

2.3. Individual assessment of risks and benefits

2.3.1. Identification and selection of nutritional, microbiological, and toxicological components of minced beef and cricket powder

The methodology applied for the identification and selection of nutrients, microbiological and toxicological components related to the consumption of beef and cricket powder has been described previously (Boué et al., 2022a,b). Briefly, for the compilation of the long list, a systematic literature review with predefined inclusion and exclusion criteria (in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines for systematic reviews), followed by standardisation of the extracted evidence was employed to identify the components of oven-dried cricket powder i.e., nutrients, nutrient-related compounds, microbiological and toxicological components (Ververis et al., 2022). The respective components of minced beef were identified in national food composition tables and databases concerning microbiological and chemical hazards (Naska et al., 2022). Subsequently, the identified components were ranked, following the methodological framework outlined by (Boué et al.,

Table 2
Components to be included in the RBA model (short list) (adapted from Boué et al., 2022a,b).

component	Nutrition											
	Calcium	Copper	Cyanocobalamin	Fibre	Iron	Magnesium	Niacin	Selenium	Sodium	Thiamin	Total omega 6-fatty acids	Total omega-3 fatty acids
Cricket powder	x	x		x	x	x		x	x		x	x
Beef			x		x		x	x	x	x		

2022a,b), and selected for inclusion in the RBA model (Table 2). The ranking and selection process considered both the occurrence of each component in the food matrix, and the severity of the associated health outcomes ("short list"). The final selection was determined by the quality and availability of relevant data ("final list").

2.3.2. *Characterisation of beneficial and adverse health effects*

For the initially selected components (Table 2), an exhaustive list of associated health outcomes was identified (Appendix) to characterise the adverse and beneficial health effects. We solely focused on diseases (hard outcomes) taking into consideration summary reports of EU authorities (EFSA, 2017) and our literature search results. Regarding nutrition and toxicology, a bottom-up approach was followed. For each pair of component-hard outcome, the literature (PubMed) was screened to identify dose-response associations, with a preference to results of meta-analyses (literature search terms included in Appendix D - example for fibre). If there was no evidence on dose-response associations between the component and the disease under investigation, the pair (component-hard outcome) could not be considered in the assessment. In the field of nutrition, in cases where multiple dose-response meta--analyses were available, preference was given to the one with lower risk of bias and a more recent publication date. The risk of bias was assessed through the ROBIS tool (A Risk of Bias Assessment Tool for Systematic Reviews) (Whiting et al., 2016).

The ROBIS tool relies on a three-step process, involving the evaluation of relevance (when applicable), the identification of issues associated with the review process, and the assessment of the risk of bias; the latter considering the criteria used by the authors to determine study eligibility, the methods used for identifying and selecting studies, the process of data collection, the evaluation of individual study bias and the synthesis of findings.

In the field of microbiology, two distinct approaches were used to elaborate on the related health outcome(s). For beef patties, a top-to-bottom approach considered the disease incidence, the source attribution, and the patties intake. Foodborne disease estimates came from World Health Organization (WHO) Global Burden of Disease (GBD) data for *Toxoplasma gondii* and *Salmonella* spp., and from French data for *Clostridium perfringens*. For cricket powder patties, a bottom-up approach employed exposure data, using threshold and exponential dose-response models for *Bacillus cereus* and *Clostridium perfringens*, respectively. The detailed implementation is further outlined in section 2.5.

2.4. *Exposure assessment*

2.4.1. *Probabilistic determination of the concentrations of nutrients, microbiological and toxicological components*

The value of nutrients, nutrient-related compounds, and components of toxicological concern was implemented with a uniform distribution spanning the range between minimum and maximum values obtained for both minced beef and cricket powder components. Regarding beef (derived both from grass and grain-fed cattle), we used the range of the macro and micronutrients reported in the national food composition databases of Denmark (Frida) (Food data, version 4, 2019), and France (ANSES, 2020), and the numerical values in the probabilistic scenarios can be within these ranges (Naska et al., 2022). With regard to cricket powder, the respective component values were within the ranges reported for oven-dried crickets by Ververis et al. (2022).

Concerning the selected microbiological components in the insect powder, the impact of heat-induced inactivation was estimated, taking into account a boiling step upon the production process of the cricket powder, as outlined in the work of (Kooh et al., 2020). Subsequently, for non-inactivated microbiological hazards, a beta distribution was employed to implement the prevalence of potentially contaminated patties based on collected frequencies of contamination. The concentration of each hazard was modelled using a uniform distribution spanning the range between minimum and maximum concentrations.

2.4.2. *Food consumption data*

The respective beef patty intake data were retrieved from the Danish National Survey of Diet and Physical Activity (DANSDA) (Pedersen et al., 2015), the Hellenic National Nutrition and Health Survey (Magriplis et al., 2019), and the Third French Individual and National Food Consumption Survey (INCA3 survey) (ANSES, 2017). The overall daily intake (in g per day) among adult participants was estimated.

2.4.3. *Exposure calculations*

Monte Carlo simulations were used to capture the variability by selecting randomly levels in concentration distribution and multiplying with reported levels of food intake (or their associated substitute estimate with cricket powder).

2.5. *Risks and benefits characterisation*

To evaluate individual risks and benefits, we utilized dose-response estimates in combination with the exposure assessment results. In the fields of nutrition and toxicology, we estimated relative risks (RR) of disease associated with the reference scenario (RRref) and alternative scenarios (RRalt), both estimated on the basis of the same reference category of intake from the original epidemiological study using the log-linear slope and the following equations.

(i) $\beta = \ln RR_{lit.pert} / dose$

(ii) $RR_{ref} = \exp(\beta * exposure_{ref})$

(iii) $RR_{alt} = \exp(\beta * exposure_{alt})$

β: linear slope (calculated from literature data); **dose**: intake linked to a response (calculated from literature data); **$RR_{lit.\ pert}$**: the relative risk of disease associated with a food component. It is estimated through the implementation of a Pert distribution to model uncertainties, taking into consideration literature-derived point estimates as well as their lower and higher intervals (95% CI); **RR_{ref}**: the relative risk for reference scenario; **$exposure_{ref}$**: the mean intake of a component in the reference scenario; **RR_{alt}**: the relative risk for alternative scenario; **$exposure_{alt}$**: the mean intake of a component in the alternative scenario.

The yearly increase or decrease in number of cases was estimated by combining the current incidence rates per country with the Potential Impact Fraction (PIF), which represents the change in disease risk linked

Nutrition			Microbiology								Toxicology	
Total saturated fatty acids	Vitamin D3	Zinc	*Bacillus cereus*	*Clostridium botulinum*	*Clostridium perfringens*	*Cronobacter sakazakii*	*Listeria monocytogenes*	Salmonella spp.	*Staphylococcus aureus*	*Toxoplasma gondii*	Arsenic (inorganic)	PAHs
		x	x	x	x	x	x	x	x		x	
x	x	x			x		x	x	x	x		x

with an alternative scenario as compared to the reference scenario (Fig. 2). Additionally, we considered the specific national frequency of patty consumption when determining the change in the number of cases which could be attributed to the alternative scenario.

(iv) PIF = $(RR_{alt}\text{-}RR_{ref})/RR_{ref}$

(v) ΔNcases= (% of population) * $frequency_{patty}$ * PIF * incidence

PIF: potential impact fraction; **%of population:** percentage of population at risk for the health outcome under study (e.g., % of males or % of females); **$frequency_{patty}$:** the country-specific likelihood to consume patty; **incidence:** the estimate of incidence derived through the implementation of a Pert distribution to model uncertainties, taking into consideration the incident values from GBD as well as their lower and higher intervals (95% CI);

In the field of toxicology, the incidence of disease associated with different exposures to inorganic arsenic (iAs) has been estimated on the basis of literature-derived average increase in population risk per μg iAs/day (mean slope) and the country-specific life expectancy.

In the field of microbiology, two distinct approaches were employed for the two food commodities.

2.5.1. Top-to-bottom microbiological approach considering disease incidence and source attribution

For beef patties, we adopted a comprehensive top-to-bottom approach, as delineated in the methodology established by (de Oliveira Mota et al., 2020). This approach considered the current disease incidence, source attribution estimates, and proportion of beef consumed in the form of patties.

The calculation involved assessing the annual number of cases attributed to *Clostridium perfringens*, *Toxoplasma gondii* (including both congenital and acquired forms), and *Salmonella* spp. associated with beef consumption. For *Toxoplasma gondii* and *Salmonella* spp., we relied on estimates from the WHO GBD data (Havelaar et al., 2015), for the European region. In the case of *Clostridium perfringens*, we utilized estimates specific to France due to the unavailability of alternative sources.

Furthermore, we determined the proportion of foodborne disease cases linked to beef for *Toxoplasma gondii* and *Salmonella* spp. by referencing the WHO GBD Study estimates (Hoffmann et al., 2017) and, for *Clostridium perfringens*, using data from France (Fosse et al., 2008). All these estimates were modelled using a beta distribution and specifically applied to patty consumption, accounting for the ratio of patties consumed within the beef category. These consumption ratios were obtained from national dietary surveys specific to each country.

(vi) ΔNcases = -incidence of infection * attribution_proportion * $ratio_{patty/beef}$ * (% $beef_{ref}$ - % $beef_{alt}$)

Incidence of infection: number of cases due to beef per year per 100,000 individuals estimated through the implementation of a Pert distribution considering the estimate, the lower and higher boundaries (95% CI); **Attribution_proportion:** the proportion of foodborne infection attributed to the consumption of beef; **$ratio_{patty/beef}$:** beef consumed in the form of patties out of total beef consumed; **% beef:** percentage of beef in patties of reference and alternative scenarios.

2.5.2. Bottom-up microbiological approach considering threshold and exponential dose-responses

In the case of cricket powder, we adopted a bottom-up approach. The approach relied on the estimated exposure values, incorporating a threshold dose-response model for *Bacillus cereus* and an exponential dose-response model for *Clostridium perfringens*. The threshold dose-response was expressed as either a concentration limit (EFSA BIOHAZ Panel, 2016) or an exposure limit (Duc et al., 2005). We used both limits to estimate the number of *Bacillus cereus* cases, considering that each exceedance corresponds to a case. For *Clostridium perfringens*, we calculated the probability of illness and multiplied it by the population size to obtain the number of cases.

2.5.3. Overall health impact quantification in DALYs

The overall health impact for each substitution scenario was quantified through Disability-Adjusted Life Years (DALYs), a composite metric for assessing the overall burden of disease, broadly used in the RBA food field. One DALY represents one year of perfect health (no disability) lost. Data on estimates of DALYs and incident rates of selected health outcomes were drawn upon the Global Burden of Disease (GBD) database (IHME, 2020), utilizing country-specific DALYs wherever available. Additionally, demographic data pertaining to the adult populations of the respective countries were sourced from the World Health Organization's European Health for All database(HFA-DB, 2022).

2.5.4. Computation method with uncertainty and variability consideration

The RBA model was developed using the @Risk® add-in software in Microsoft Excel version 7.6 (Palisade Corporation, Ithaca, NY, USA). Monte Carlo simulations were used to capture the uncertainty and the variability of the model inputs and parameters.

3. Results

3.1. Final list of food components and associated health effects

The final list of components included calcium, cyanocobalamin (vitamin B12), fibre (insoluble), iron, magnesium, sodium, and zinc as nutrition-related components (Appendix A). In terms of microbiological hazards, *Bacillus cereus*, *Clostridium perfringens*, *Cronobacter sakazakii*, *Listeria monocytogenes*, *Salmonella* spp., and *Toxoplasma gondii* were included (Appendix B). Among the toxicological hazards, only inorganic arsenic was included (Appendix C). Copper and *Clostridium botulinum* were excluded due to the lack of dose-response epidemiological data. Niacin, thiamin, and vitamin D3, initially in the short list based on beef, were omitted from the final selection due to the absence of corresponding data for oven-dried cricket powder. Although literature data were available for other forms of dried crickets (Ververis et al., 2022), we refrained from extrapolation due to the unpredictability of losses during thermal processing, to reduce uncertainty in the findings.

Additionally, selenium was excluded because preliminary calculations indicated that the overall daily selenium intake would not exceed 60 μg/day in any of the alternative scenarios, a value which is below the level at which selenium intake has been associated with an increased risk of type 2 diabetes (Vinceti et al., 2021). Lastly, polyunsaturated fatty acids (mainly n-6) and saturated fatty acids were not included in

Table 3
Final selection of components to be included in the RBA model and associated health outcomes.

component		cricket powder	beef	health outcome(s)	Type and source of (dose-response) data	Risk of bias
Nutrition	Calcium	x		Breast cancer	Meta-analysis of epidemiological studies (Hidayat et al., 2016)	low
				Prostate cancer	Meta-analysis of epidemiological studies (Aune et al., 2015)	high
				Colorectal cancer	Meta-analysis of epidemiological studies (Huang et al., 2020)	unclear/ low
	Cyanocobalamin		x	Oesophageal cancer	Meta-analysis of epidemiological studies (Qiang et al., 2018)	high
				Colorectal cancer	Meta-analysis of epidemiological studies (Sun et al., 2015)	unclear
	Fibre	x		Coronary Heart Disease (CHD)	Meta-analysis of epidemiological studies (Reynolds et al., 2019)	low
				Colorectal cancer	Meta-analysis of epidemiological studies (Reynolds et al., 2019)	low
				Chron's disease	Meta-analysis of epidemiological studies (Liu et al., 2015)	high
				Cardiovascular Disease (CVD)	Meta-analysis of epidemiological studies (Threapleton et al., 2013)	low
				Diabetes mellitus type II	Meta-analysis of epidemiological studies (Reynolds et al., 2019)	low
				Oesophageal cancer	Meta-analysis of epidemiological studies (Sun et al., 2017)	low
				Gastric cancer	Meta-analysis of epidemiological studies (Zhang et al., 2013a)	low
				Ovarian cancer	Meta-analysis of epidemiological studies (Zheng et al., 2018)	low
				Pancreatic cancer	Meta-analysis of epidemiological studies (Mao et al., 2017)	low
				Stroke	Meta-analysis of epidemiological studies (Zhang et al., 2013b)	low
				Breast cancer	Meta-analysis of epidemiological studies (Chen et al., 2016)	low
	Iron	x	x	Oesophageal cancer	Meta-analysis of epidemiological studies (Ma et al., 2018)	low
	Magnesium	x		Diabetes mellitus type II	Meta-analysis of epidemiological studies (Fang et al., 2016)	low
	Sodium	x	x	CVD	Meta-analysis of epidemiological studies (Wang et al., 2020)	low
	Zinc	x	x	Oesophageal cancer	Meta-analysis of epidemiological studies (Ma et al., 2018)	low
Microbiology	*Bacillus cereus*	x		Emetic symptoms (nausea, vomiting, discomfort, diarrhoea, and occasional abdominal pain); Diarrheal symptoms (watery diarrhoea, abdominal pains, occasional nausea)	Comparison with a threshold dose-response (EFSA BIOHAZ Panel, 2016; Duc et al., 2005)	n.a.
	Clostridium perfringens	x	x	Diarrhoea, severe stomach pain, nausea, vomiting, fever	Exponential dose-response (cricket powder) (Golden et al., 2009)	n.a.
					Source attribution (beef) (de Oliveira Mota et al., 2020)	n.a.
	Cronobacter sakazakii	x		Abscesses, colonization, bacteraemia, osteomyelitis, pneumonia, urinary tract infections, ulcers	Calculation of heat treatment inactivation (cricket powder) (Kooh et al., 2019)	n.a.
	Listeria monocytogenes	x	x	Maternal neonatal forms [flu-like symptoms (fever, chills, back pain), miscarriage, death in utero, prematurity - neonatal infection);	Calculation of heat treatment inactivation (cricket powder) (Kooh et al., 2019)	n.a.
				Non-maternal neonatal forms (septicaemia/bacteraemia, meningitis, meningoencephalitis, rhombencephalitis, brain abscess, local infections);	Calculation of heat treatment inactivation (cricket powder) (Kooh et al., 2019)	n.a.
				Gastroenteric forms (fever, nausea, vomiting, diarrhoea)	Calculation of heat treatment inactivation (cricket powder) (Kooh et al., 2019)	n.a.
	Salmonella spp.	x	x	Non-typical Salmonellosis (Nausea, vomiting, Abdominal pain, Diarrhoea, Headache, Chills, Fever),	Calculation of heat treatment inactivation (cricket powder) (Kooh et al., 2019)	n.a.
				Typhoid fevers (prolonged fever, intense headache, anorexia, constipation or diarrhoea, drowsiness, prostration during the day, insomnia at night, pinkish macules on flanks or chest)	Source attribution (beef) (de Oliveira Mota et al., 2020)	n.a.
	Toxoplasma gondii		x	Mild effects (cervical or occipital adenopathy, fever, myalgia, asthenia);	Source attribution (beef) (de Oliveira Mota et al., 2020)	n.a.
				Severe effects (pulmonary, neurological, or disseminated toxoplasmosis following contamination with virulent genotype);	Source attribution (beef) (de Oliveira Mota et al., 2020)	n.a.
				Ocular effects (chorioretinitis in variable locations progressing to spontaneous healing)	Source attribution (beef) (de Oliveira Mota et al., 2020)	n.a.

(*continued on next page*)

Table 3 (*continued*)

component		cricket powder	beef	health outcome(s)	Type and source of (dose-response) data	Risk of bias
Toxicology	Arsenic (inorganic)	x		Bladder cancer	Slope factor for arsenic-related bladder cancer (Oberoi et al., 2019)	n.a.
				Lung cancer	Slope factor for arsenic-related lung cancer (Oberoi et al., 2019)	n.a.
				Skin cancer	Slope factor for arsenic-related skin cancer (Oberoi et al., 2019)	n.a.

n.a. not applicable.

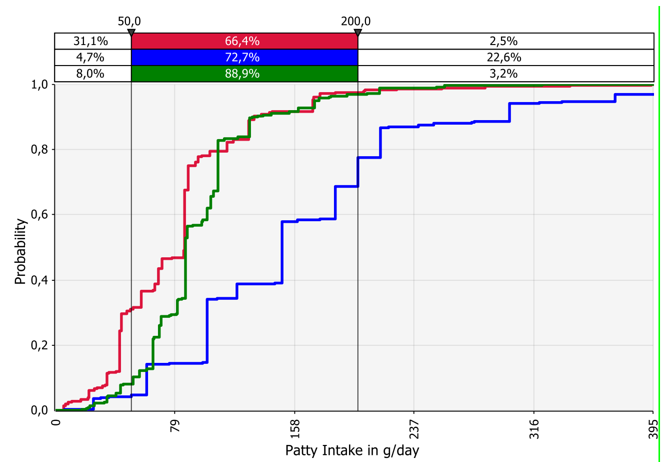

Fig. 3. Cumulative distribution of current intake of minced beef patties (in grams per day) in Denmark (blue), France (green), and Greece (red). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 4
Intake of beef and cricket powder via the consumption of patties.

Country	Scenario	Beef (g/day)			Cricket powder (g/day)		
		P2.5	Median	P97.5	P2.5	Median	P97.5
Denmark	Ref	22.5	135.0	387.0	0.0	0.0	0.0
	A1[a]	0.0	0.0	0.0	4.5	27.0	77.4
	B1[a]	11.3	67.5	193.5	2.3	13.5	38.7
	A2[b]	0.0	0.0	0.0	9.0	54.0	154.8
	B2[b]	11.3	67.5	193.5	4.5	27.0	77.4
France	Ref	30.9	77.1	192.9	0.0	0.0	0.0
	A1[a]	0.0	0.0	0.0	6.2	15.4	38.6
	B1[a]	15.4	38.6	96.4	3.1	7.7	19.3
	A2[b]	0.0	0.0	0.0	12.3	30.9	77.1
	B2[b]	15.4	38.6	96.4	6.2	15.4	38.6
Greece	Ref	7.4	76.6	183.1	0.0	0.0	0.0
	A1[a]	0.0	0.0	0.0	1.5	15.3	36.6
	B1[a]	3.7	38.3	91.5	0.7	7.7	18.3
	A2[b]	0.0	0.0	0.0	3.0	30.6	73.2
	B2[b]	3.7	38.3	91.5	1.5	15.3	36.6

- Reference scenario: 90% minced beef and 10% other ingredients.
- Substitution scenario A: 90% cricket "dough" and 10% other ingredients.
- Substitution scenario B: 45% minced beef, 45% cricket "dough" and 10% other ingredients.

[a] "Dough" cricket powder-to-water ratio = 20:80.
[b] "Dough" cricket powder-to-water ratio = 40:60.

the final list due to the contentious nature of available epidemiological data on their overall health effects (particularly in relation to inflammation, cardiovascular disease, and overall metabolic health). Scientific debates persist regarding the optimal intake levels and sources of these fatty acids, highlighting the need for further research to clarify their effects.

The decision to exclude *Staphylococcus aureus* (enterotoxin) from the final list was based on the lack of available data concerning its concentration and prevalence in cricket powder, coupled with the relatively low public health concern associated with the consumption of minced beef patties (Pires et al., 2012).

Furthermore, polycyclic aromatic hydrocarbons (PAHs) were not considered, assuming that minced beef- and insect-containing patties would undergo the same cooking method.

Table 3 provides a comprehensive overview of the health outcomes associated with the selected food components, alongside details on the source of the dose-response data and risk of bias assessments. Certain components listed were chosen specifically for either the cricket powder or beef, while others like iron, sodium, or *C. perfringens* were selected due to their importance for both food items.

Within the domain of nutrition, the majority of studies were of low risk of bias. Two meta-analyses, however, exploring the dose-response relationship between dietary calcium intake and prostate cancer (Aune et al., 2015), as well as cyanocobalamin intake and oesophageal cancer (Qiang et al., 2018), were identified as having a high risk of bias.

3.2. Exposure assessment of reference and alternative scenarios

Using individual food consumption data collected according to the EFSA EU Menu methodology, a standardized approach developed by EFSA for collecting individual food consumption data across EU member states (Ioannidou et al., 2020), the cumulative distribution of the current intake of minced beef patties was calculated for the adult populations of Denmark, France, and Greece (Fig. 3). The intake variability, both among the three countries and within individuals is depicted.

Based on current food consumption data and on recipes (Fig. 2), the cricket powder intake in the four substitution scenarios were estimated for each country. The results are presented in Table 4. The highest median intake of beef through the consumption of patties was observed in Denmark (135g/day), while the median intakes of France and Greece were almost similar (~77g/day).

The daily exposure values of nutrients, nutrient-related components, and components of toxicological concern that were included in the RBA model are presented in Table 5, for all counties, both for the reference and alternative scenarios. From a qualitative point of view, the same increase or decrease trends with regard to the intake of nutrients, nutrient-related components, and components of toxicological concern are observed among all countries. Moving from the reference to any of the alternative scenarios resulted in substantial increase in calcium, fibre, magnesium, and inorganic arsenic intake. On the opposite, vitamin B12 intake decreased in all substitution scenarios.

Iron reduced in scenarios A1 and B1, whereas scenarios A2 and B2 led to a slight increase of the iron intake, compared to the reference scenario. Similarly, sodium and zinc intakes are decreased in scenarios A1 and B1, and increased in scenarios A2 and B2, compared to the reference scenario.

In Table 6, the mean probability of infection associated with microbiological hazards from cricket powder consumption is presented across scenarios A1, B1, A2, and B2. Concerning *B. cereus* infection, this mean probability ranges from 0 to 4.7E-02, with the highest value observed in France for scenario A2. This wide uncertainty interval stems from the lack of a definitive dose-response relationship for *B. cereus,*

Table 5
Daily exposure values of included nutrients, nutrient-related components, and components of toxicological concern for reference and alternative scenarios.

Scenario	Reference			A1			B1			A2			B2		
minced beef (%)	90			0			45			0			45		
cricket powder (%)	0			18			9			36			18		
other ingredients (%)	10			10			10			10			10		
water (from the "dough")	0			72			36			54			27		
Percentile	P2.5	P50	P97.5	P2.5	P50	P97.5	P2.5	P50	P97.5	P2.5	P50	P97.5	P2.5	P50	P97.5
Denmark															
Calcium (mg/day)	2.52	13.67	45.03	8.49	48.67	132.47	5.49	31.68	86.26	16.97	97.34	264.94	9.74	56.22	152.12
Cyanocobalamin (μg/day)	0.49	2.53	7.93	0.02	0.10	0.26	0.25	1.31	4.08	0.03	0.19	0.51	0.26	1.35	4.18
Fibre (g/day)	0.00	0.00	0.00	0.35	1.89	5.52	0.18	0.94	2.76	0.71	3.78	11.03	0.35	1.89	5.52
Iron (mg/day)	0.62	3.20	9.69	0.31	1.67	4.87	0.46	2.53	7.16	0.62	3.33	9.74	0.60	3.42	9.52
Magnesium (mg/day)	4.79	27.47	74.67	5.30	30.30	82.66	4.94	29.04	78.01	10.59	60.60	165.32	7.59	44.42	118.86
Sodium (mg/day)	14.65	77.91	228.92	11.03	57.36	184.67	12.61	70.11	199.09	22.06	114.72	369.34	18.27	98.63	287.87
Zinc (mg/day)	1.08	5.99	16.72	0.83	4.66	12.89	0.93	5.42	14.65	1.66	9.33	25.78	1.34	7.79	21.02
Arsenic - inorganic (μg/day per Kg bw)	0.00	0.01	0.04	0.01	0.15	0.59	0.01	0.08	0.31	0.02	0.29	1.18	0.01	0.15	0.60
France															
Calcium (mg/day)	2.37	8.38	23.13	9.52	28.55	66.73	6.28	18.62	43.77	19.05	57.11	133.45	11.10	33.04	76.88
Cyanocobalamin (μg/day)	0.47	1.55	4.11	0.02	0.06	0.13	0.25	0.80	2.11	0.04	0.11	0.26	0.26	0.83	2.17
Fibre (g/day)	0.00	0.00	0.00	0.37	1.14	2.87	0.18	0.57	1.43	0.74	2.28	5.73	0.37	1.14	2.87
Iron (mg/day)	0.62	1.97	5.04	0.33	1.01	2.53	0.50	1.51	3.66	0.65	2.01	5.06	0.67	2.02	4.86
Magnesium (mg/day)	5.39	16.11	37.68	5.94	17.77	41.75	5.87	17.03	39.46	11.88	35.54	83.50	8.86	26.07	60.07
Sodium (mg/day)	15.29	47.15	118.59	10.28	35.13	94.94	13.71	41.86	101.99	20.56	70.27	189.88	19.19	59.47	147.77
Zinc (mg/day)	1.17	3.53	8.55	0.91	2.74	6.55	1.08	3.18	7.41	1.83	5.48	13.10	1.55	4.57	10.64
Arsenic - inorganic (μg/day per Kg bw)	0.00	0.01	0.02	0.01	0.10	0.34	0.01	0.05	0.18	0.01	0.20	0.67	0.01	0.10	0.35
Greece															
Calcium (mg/day)	0.92	6.54	23.08	3.02	24.04	65.38	1.97	15.82	42.77	6.04	48.07	130.76	3.47	27.97	74.95
Cyanocobalamin (μg/day)	0.17	1.23	4.11	0.01	0.05	0.12	0.09	0.64	2.11	0.01	0.10	0.24	0.09	0.67	2.18
Fibre (g/day)	0.00	0.00	0.00	0.13	0.94	2.86	0.06	0.47	1.43	0.26	1.88	5.72	0.13	0.94	2.86
Iron (mg/day)	0.22	1.60	5.06	0.11	0.83	2.53	0.16	1.26	3.63	0.22	1.66	5.06	0.22	1.70	4.80
Magnesium (mg/day)	1.71	13.57	36.90	1.88	14.96	40.91	1.76	14.69	37.82	3.77	29.91	81.83	2.69	22.27	57.82
Sodium (mg/day)	5.29	38.80	118.74	3.95	27.44	94.96	4.55	34.95	101.04	7.91	54.87	189.92	6.57	49.04	146.91
Zinc (mg/day)	0.38	2.94	8.47	0.29	2.29	6.48	0.33	2.71	7.20	0.59	4.59	12.95	0.48	3.90	10.33
Arsenic - inorganic (μg/day per Kg bw)	0.00	0.01	0.02	0.00	0.08	0.32	0.00	0.04	0.17	0.01	0.15	0.63	0.01	0.08	0.32
(shaded)	increase compared to the reference scenario														

Table 6
Mean probability of B. cereus *C. perfringens* infection associated with cricket powder consumption.

	Probability of illness			
	Scenario A1	Scenario B1	Scenario A2	Scenario B2
Denmark				
B. cereus	[0.0E+00; 3.5E-02]	[0.0E+00; 3.3E-03]	[0.0E+00; 1.3E-01]	[0.0E+00; 3.5E-02]
C. perfringens	1.2E-08	5.8E-09	2.3E-08	1.2E-08
France				
B. cereus	[0.0E+00; 4.0E-03]	[0.0E+00; 4.3E-05]	[0.0E+00; 4.7E-02]	[0.0E+00; 4.0E-03]
C. perfringens	6.8E-09	3.4E-09	1.4E-08	6.8E-09
Greece				
B. cereus	[0.0E+00; 4.2E-03]	[0.0E+00; 2.1E-04]	[0.0E+00; 3.6E-02]	[0.0E+00; 4.2E-03]
C. perfringens	5.8E-09	2.9E-09	1.2E-08	5.8E-09

[a] "dough" cricket powder-to-water ratio = 20:80.
[b] "dough" cricket powder-to-water ratio = 40:60.
- Reference scenario: 90% minced beef and 10% other ingredients.
- Substitution scenario A: 90% cricket "dough" and 10% other ingredients.
- Substitution scenario B: 45% minced beef, 45% cricket "dough" and 10% other ingredients.

while a specific dose-response was applied for *C. perfringens* (section 2.5.2). Comparing the mean probability of illness for *B. cereus* (the higher value) and the reported values for *C. perfringens*, scenario B1 has the lowest probability of infection across all countries, followed by scenarios A1 and B2 (which are equal), and then scenario A2. These probabilities are consistent with the levels of cricket powder intake outlined in Table 5. Increasing the level of exposure to cricket powder directly correlates with a higher probability of illness.

Table 7
Total Δ DALY per 100,000 person-years and per country's total population.

	Scenario	A1			B1			A2			B2		
Ingredients	minced beef (%)	0			45			0			45		
	cricket powder (%)	18			9			36			18		
	other ingredients (%)	10			10			10			10		
	Water (from the "dough")	72			36			54			27		
	DALYs	Denmark	France	Greece	Denmark	France	Greece	Denmark	France	Greece	Denmark	France	Greece
per 100000 persons	Nutrition	-74.95	-55.4	-98.38	-47.9	-32.35	-56.39	1189.81	342.24	505.91	247.28	107.08	170.28
	Toxicology	-0.03	-0.02	-0.01	-0.01	-0.01	-0.01	-0.05	-0.04	-0.03	-0.03	-0.02	-0.01
	Microbiology	-11.27	-11.73	-1.57	-5.53	-5.83	-0.77	-10.73	-11.44	-1.35	-4.99	-5.53	-0.55
	Total mean	-86.25	-67.15	-99.96	-53.45	-38.18	-57.17	1179.03	330.77	504.52	242.27	101.53	169.71
	Total P5	-104.37	-86.75	-128.01	-68.36	-51.08	-77.85	218.34	86.92	155.71	71.13	33.51	64.1
	Total P50	-85.23	-66.38	-99.87	-53.24	-38	-57.12	1178.33	330.59	504.2	242.1	101.46	169.6
	Total P95	-60.07	-43.3	-60.68	-33.55	-23.2	-32.37	4664	840.62	1159.8	563.85	198.56	312.61
per country's total population	Nutrition	-3617.15	-29375.07	-9027.92	-2311.77	-17153.83	-5174.52	57420.49	181483.3	46425.08	11933.75	56783.3	15625.98
	Toxicology	-1.27	-9.34	-1.31	-0.64	-4.67	-0.66	-2.65	-19.42	-2.73	-1.33	-9.71	-1.36
	Microbiology	-1034.53	-1076.65	-144.1	-507.81	-534.72	-70.74	-984.34	-1049.51	-124.13	-457.62	-507.58	-50.77
	Total mean	-4652.95	-30461.06	-9173.34	-2820.22	-17693.22	-5245.92	56433.5	180414.37	46298.23	11474.8	56266.01	15573.84
	Total P5	-6000.85	-38397.97	-11746.59	-3697.34	-23839.7	-7143.94	10061.39	51244.57	14288.92	3206.11	20309.51	5881.85
	Total P50	-4516.44	-30403.74	-9164.55	-2788.43	-17671.51	-5241.85	56400.95	180271.78	46268.61	11470.13	56219.72	15563.49
	Total P95	-3202.57	-18989.85	-5568.77	-1785.68	-10196.86	-2970.31	224625.52	450661.92	106430.77	27003.08	107636.22	28686.63
(green)		ΔDALY < 0											
(yellow)		ΔDALY > 0											

Table 8
Mean percentage contribution of each component to the total ΔDALY when moving from the reference to the alternative scenarios.

	A1[a]			B1[a]			A2[b]			B2[b]		
minced beef (%)	0			45			0			45		
cricket powder (%)	18			9			36			18		
other ingredients (%)	10			10			10			10		
water from the "dough" (%)	72			36			54			27		
	Denmark	**France**	**Greece**	**Denmark**	**France**	**Greece**	**Denmark**	**France**	**Greece**	**Denmark**	**France**	**Greece**
NUTRITION												
Calcium	0.08	0.07	0.04	0.07	0.06	0.03	0.01	0.03	0.02	0.04	0.05	0.02
Cyanocobalamin	1.05	0.69	0.44	1.03	0.71	0.38	0.07	0.12	0.08	0.2	0.22	0.11
Fibre	9.38	7.1	7.95	7.65	6.28	7	1.33	2.57	2.94	3.09	3.94	4.28
Iron	0.3	0.23	0.05	0.23	0.2	0.04	0	0	0	0	0	0
Magnesium	0.05	0.03	0.03	0.04	0.03	0.03	0.04	0.07	0.07	0.1	0.11	0.1
Sodium	75.8	74.53	89.84	80.03	77.47	91.04	97.51	93.89	96.54	94.08	90.55	94.9
Zinc	0.25	0.19	0.04	0.2	0.17	0.03	0.04	0.08	0.02	0.09	0.13	0.02
MICROBIOLOGY												
B. cereus	0.23	0.04	0.03	0.37	0.07	0.05	0.06	0.09	0.05	0.28	0.26	0.13
C. perfringens	0.66	0.88	0.49	0.53	0.77	0.43	0.05	0.16	0.09	0.11	0.24	0.13
Salmonella spp.	9.83	13.12	0.88	7.93	11.53	0.77	0.71	2.4	0.16	1.62	3.64	0.24
T. gondii	2.33	3.12	0.21	1.88	2.67	0.18	0.17	0.57	0.04	0.38	0.84	0.06
TOXICOLOGY												
Arsenic (inorganic)	0.03	0.03	0.01	0.02	0.02	0.01	0	0.01	0.01	0.01	0.01	0.01

- Reference scenario: 90% minced beef and 10% other ingredients.
- Substitution scenario A: 90% cricket "dough" and 10% other ingredients.
- Substitution scenario B: 45% minced beef, 45% cricket "dough" and 10% other ingredients.

[a] "Dough" cricket powder-to-water ratio = 20:80.
[b] "Dough" cricket powder-to-water ratio = 40:60.

3.3. Overall health impact estimated

The overall health impact estimated in DALYs, for each substitution scenario, is presented in Table 7 per country, taking into account differences in national dietary intakes. The changes can be primarily attributed to the nutritional and microbiological alterations resulting within the investigated dietary substitution scenarios. Shifting from the reference to the alternative scenarios A1 or B1 results to a beneficial public health impact (ΔDALY<0) in all countries, with the shift to A1 being more favourable. Greece is the most favoured among the three countries (ΔDALY per 100,000 persons). On the contrary, shifting from the reference scenario to the alternative scenarios A2 or B2 results to a negative public health impact (ΔDALY>0) in all countries. The worst case appears to be the shift to scenario A2 (beef fully substituted with cricket "dough" with elevated cricket level), with Denmark being the most negatively impacted among the three countries.

3.3.1. The contribution of components to the overall health impact

Table 8 presents the mean percentage of contribution of each component to the total ΔDALY when moving from the reference to the

Table 9
Total ΔDALY per 100,000 person-years and per country's total population, with the effect of sodium excluded.

		A1			B1			A2			B2		
	minced beef (%)	0			45			0			45		
	cricket powder (%)	18			9			36			18		
	other ingredients (%)	10			10			10			10		
	water from the "dough" (%)	72			36			54			27		
	DALYs	Denmark	France	Greece	Denmark	France	Greece	Denmark	France	Greece	Denmark	France	Greece
per 100000 persons	Nutrition	-7.09	-4.18	-7.58	-3.5	-2.07	-3.82	-16.75	-9.87	-16.01	-8.48	-4.96	-8.1
	Toxicology	-0.03	-0.02	-0.01	-0.01	-0.01	-0.01	-0.05	-0.04	-0.03	-0.03	-0.02	-0.01
	Microbiology	-11.27	-11.73	-1.57	-5.53	-5.83	-0.77	-10.73	-11.44	-1.35	-4.99	-5.53	-0.55
	Total mean	-18.39	-15.93	-9.16	-9.05	-7.9	-4.59	-27.54	-21.34	-17.39	-13.49	-10.51	-8.67
	Total P5	-31.99	-29.86	-10.79	-15.85	-14.43	-5.41	-41.24	-35.28	-19.93	-20.38	-17.04	-9.98
	Total P50	-16.88	-14.37	-9.15	-8.29	-7.22	-4.58	-26.08	-19.8	-17.41	-12.79	-9.84	-8.68
	Total P95	-10.01	-7.42	-7.7	-4.85	-3.76	-3.86	-18.89	-12.76	-14.98	-9.11	-6.33	-7.42
per country's total population	Nutrition	-342.39	-2218.46	-695.59	-168.88	-1096.35	-350.11	-808.53	-5234.23	-1469.09	-409.25	-2632.26	-743.17
	Toxicology	-1.27	-9.34	-1.31	-0.64	-4.67	-0.66	-2.65	-19.42	-2.73	-1.33	-9.71	-1.36
	Microbiology	-1034.53	-1076.65	-144.1	-507.81	-534.72	-70.74	-984.34	-1049.51	-124.13	-457.62	-507.58	-50.77
	Total mean	-1378.19	-3304.45	-841.01	-677.33	-1635.74	-421.51	-1795.52	-6303.16	-1595.94	-868.2	-3149.55	-795.3
	Total P5	-2623.46	-4619.97	-989.76	-1300.21	-2257.64	-496.4	-3043.99	-7711.38	-1828.54	-1494.79	-3823.79	-915.62
	Total P50	-1237.48	-3181.9	-839.32	-607.29	-1583.23	-420.74	-1657.27	-6213.77	-1597.4	-800.61	-3113.81	-796.33
	Total P95	-615.34	-2428.37	-706.78	-295.62	-1208.91	-354.06	-1024.19	-5250.11	-1374.35	-476.77	-2630.82	-681.32
		ΔDALY < 0											

alternative scenarios A1, B1, A2, or B2. The main influencing factor of the overall health impact is sodium, having a mean contribution to the total ΔDALY that spans from 74.53 to 97.51% across the various scenarios investigated. Fibre accounts for 1.33–9.38% of the total ΔDALY in the different scenarios. Compared to sodium, the rest of the model components have a substantially lower contribution to the ΔDALY. It should be noted though that the reduction of risks of salmonellosis has various contribution percentages among the different scenarios, which range from very low (0.16%) up to substantial contribution (13.12%).

To investigate further the impact of sodium on the overall outcome, we simulated the substitution scenarios by excluding the sodium and the related health effects from the RBA model. The overall health impact, without considering the effect of sodium, is presented in Table 9, for each country. Interestingly, the overall health impact of all substitution scenarios is positive in every case, for all countries. The contributions of nutrition and microbiology to the mean total ΔDALY become of the same magnitude for France and Denmark. However, in the case of Greece, the nutrition domain remains the main one shaping the overall health impact.

4. Discussion

4.1. Summary of findings

Using RBA methods, this study assessed the impact on public health of substituting red meat, a dietary staple in Europe, by insects. The RBA question focused on replacing beef with cricket powder in burger patties for the Danish, French and Greek adult populations, representing a research topic highly relevant in the context of shifting dietary patterns within Europe in response to health, environmental and ethical considerations. Our study revealed that the investigated dietary shift can exhibit varying impacts on health overall influenced by the specific recipe formulations used as well as by the hydration percentage of cricket powder utilized, with sodium being the principal component shaping the results. The results emphasize that the effects on public health outcomes span a spectrum rather than conforming to dichotomous categorizations.

The selection of the food forms (patties) and the formulation of recipes, both for the reference and alternative substitution scenarios, aimed to replicate food preparation practices and investigate the extreme cases. The way of integrating insect-derived ingredients into diets, especially in western societies, is crucial, as consumer acceptance of edible insects often hinge on familiarity, palatability and food neophobia (Boehm et al., 2021). Furthermore, considering two different hydration compositions of the cricket powder, 20% and 40% offered additional insights into the potential role of food processing and recipe formulation in relation to public health.

Our study employs a comprehensive RBA approach, covering nutrients, microbiological and toxicological hazards in minced beef and cricket powder. Using the extensive compositional profiling of these two foods and applying the recently developed methodological framework of Boué et al., 2022a,b, a harmonised list of nutritional, microbiological, and toxicological components to be included in the RBA model. The fact that cricket powder is a novel food generated additional challenges as data on levels of toxicological and microbiological agents, and nutrients were scattered and not necessarily readily comparable.

Each of the selected components was linked to at least one health effect (hard outcomes). Systematic literature reviews and risk of bias assessment offer a solid foundation for evaluating the holistic health implications of the dietary substitution. The common metric used to express the overall health impact was the DALYs.

According to our results, substitution of beef patties by insect patties can have a beneficial or an adverse overall health impact, depending on the scenario setting (recipe used to incorporate the cricket powder in the final product), as well as on the hydration percentage of the cricket powder. The shift from the reference to the substitution scenarios A1 or B1 lead to a positive for the public health outcome Notwithstanding, scenarios A2 and B2 do not represent beneficial alternatives for public health.

In cases for which the health impact of the substitution is not favourable, the main contributor is the presence of sodium in the cricket powder. It has been reported that sodium is an essential micronutrient for the growth and survival of crickets, thus it is intrinsically present in the cricket powder (Luckey and Stone, 1968). The production of meat preparations (i.e., hybrid products containing meat) and meat analogues (i.e., products devoid of meat yet designed to simulate its presence), whether undertaken domestically or industrially, may entail the inclusion of added sodium, on top of the sodium naturally inherent in the raw materials, due to the use of salt in their preparation. In our study, we assumed that 10% of the ingredients in the patties (including any eventually added salt) remained common and unchanged for all the scenarios, comparing thus solely the minced beef and cricket powder as raw materials.

4.2. The importance of the recipe and the food comparators

While cricket powder contains substantial amounts of sodium, it is possible to design recipes (scenarios A1 and B1) in which the overall sodium intake decreases. These scenarios involve a lower cricket powder content (20%) in the insect dough mixture. To elucidate this aspect further, we simulated the substitution scenario by excluding the sodium and the related health effects from the RBA model (Table 9). The results then suggested a positive health impact of all substitution scenarios, in all three countries. These findings highlight the need to design and formulate new food products using less salt (NaCl) towards a reduced intake of sodium, in accordance with salt-related food reformulations suggested in the literature (Marakis et al., 2023). There is indeed a growing interest in the field of food reformulation, towards improving the nutrient profile of foods or reducing the content of food components of health concern (WHO, 2022). Novel food ingredients, such as cricket powder, could potentially contribute to achieving such goals. On this note, it is imperative to explore dietary modifications for crickets to mitigate their sodium accumulation to the extent possible.

With regard to incorporating cricket powder, a novel ingredient subject to Regulation (EU) 2015/2283, into food products, consideration of the EU permitted incorporation levels during the preparation/manufacturing of new products is required. Our study investigated two types of food products, the “meat analogues” (A1, A2) and the “meat preparations” (B1, B2). For meat analogues, in which no meat is present, the current maximum EU permitted level for whole cricket powder is 50%. In our study, we explored 18% (A1) and 36% (A2). In contrast, for meat preparations, where meat is included, the permitted level is lower at 16%. Our investigation covered levels of 9% (B1) and 18% (B2) cricket powder, with B2 level being slightly above the current EU limit.

On top of the regulatory requirements, it should be noted that food technological parameters should be considered. There are studies in the literature that investigated the percentage of inclusion of insect powder in “hybrid” meat preparations. (Kim et al., 2017) suggested that cricket powder up to 10% can be used to manufacture emulsified meat products. (Cavalheiro et al., 2023; Han et al., 2023) investigated how the addition of cricket powder in hybrid meat sausages impacts the nutritional, structural, technological, sensorial, and stability profile of such products, revealing technological limitations with regard to the maximum levels of inclusion. Similar studies have been previously performed with other insect-derived powders too, e.g., of yellow mealworm and silkworm pupae (Choi et al., 2017; Kim et al., 2016).

4.3. Relevant components not included in the RBA model

Copper and *Clostridium botulinum* were not included in the model, even if marked as relevant, due to the lack of dose-response epidemiological data for copper and prevalence and concentration for *Clostridium botulinum*. Additionally, the exclusion of niacin, thiamin, and vitamin D3, initially considered based on beef meat, highlights the necessity for comprehensive data specific to oven-dried cricket powder, as extrapolation from other dried cricket forms would introduce uncertainty due to potential losses during thermal processing. The decision to omit polyunsaturated fatty acids and saturated fatty acids reflects the ongoing debate surrounding their overall health effects. As reviewed by (Ververis et al., 2022), dried *A. domesticus* contains substantial levels of polyunsaturated fatty acids (PUFAs), with the n-6 PUFAs prevailing over the n-3 PUFA though (12–40 folds higher). Since high amounts of n-6 PUFAs are not beneficial for human health, the dietary substitution of the beef-derived saturated fat by the cricket-derived PUFAs could not readily be introduced in the RBA model, due to the aforementioned controversy and the lack of data.

The inclusion and exclusion of components in an RBA can possibly affect the final outcome, thus a transparent documentation of all the decisions made and actions taken in each step is necessary and needs to be documented alongside the numerical results, to strengthen further the assessment’s completeness.

4.4. Strengths and limitations

To our knowledge, the available literature investigating the overall health impact of substituting red meat by insects is limited. A study by (Orkusz, 2021) performed a comparison of different meat types and insect species based solely on their nutrient composition. To date, the application of RBA to investigate the substitution of meat by novel proteins remains still in its nascent stages, with only preliminary results being published by (Naska et al., 2022). Previous RBAs have examined the substitution of red meat by other staple foods, i.e., fish (Thomsen et al., 2018, 2019) and pulses (Fabricius et al., 2021), all focusing to the Danish diet.

The present study exhibits several notable strengths that enhance its significance and contribution to the field of RBA and dietary assessment in general. It constitutes a comprehensive exploration of the overall health implications of consuming edible insects as a replacement for red meat. In contrast to previous comparisons employing more simplistic approaches, our multifaceted methodology factors in various elements, such as diverse types of compositional data (nutrition, microbiology, toxicology), various food product formulations, individual dietary intakes, and data quality controls. Moreover, we adopted a probabilistic approach in our model, aligning with contemporary methodologies in RBA (Pires et al., 2019). This decision not only adds to the robustness of our findings but also enhances their reliability. The RBA model implemented exhibits versatility allowing for the incorporation of updated data and newly emerging information, facilitating meaningful comparisons. The core of our RBA model is the harmonised and transparent selection of components and health effects, incorporating factors such as occurrence and severity of the respective health outcomes (Boué et al., 2022a,b).

Nevertheless, while providing valuable insights, the study is not without its limitations. Firstly, some assumptions (i.e., types of distributions of components, prevalence of *C. perfringens* and *B. cereus* in crickets) were necessary for our modelling, introducing a degree of uncertainty into the results. Additionally, there was a notable absence of data and dose-response information for specific components, emphasizing the need for further research and data collection in these areas. When interpreting the results, it is important that such limitations are acknowledged. Another factor to be considered is that the component-based approach we followed, “imposed” by the novelty of one of the comparators, may hinder some assumptions. For example, we included in our model health effects related to insoluble fibre from other sources (e.g., fruits, vegetables). In *A. domesticus*, the main form of fibre is chitin, and it is not yet clear whether chitin has exactly the same effect as other types of dietary fibre. In the same line, it should be highlighted that the absence of considerations for the matrix effect (the whole food) is another point of limitation. However, such approach had to be followed, since cricket powder is a novel food and epidemiological studies with this food commodity do not exist. Furthermore, it should be acknowledged that, despite assuming equivalent occurrence of PAHs in both minced beef- and insect-containing patties subjected to the same cooking method (thus leading to their exclusion from the list of components included in the RBA), differences in the final levels of PAHs in the cooked foods may arise due to the matrix effect. Moreover, allergenicity aspects were not included in the RBA model. However, it should be acknowledged that incorporating allergenicity, even in the classical risk assessment of novel proteins, remains a challenging point (Fernandez et al., 2021; Verhoeckx et al., 2020; Ververis et al., 2020).

Lastly, we acknowledge the distinction between hard endpoints and markers of disease, which should be considered when extrapolating our results to real-world health implications. These limitations indicate areas for further research and refinement in the field of dietary impact assessment.

5. Conclusions

This study presents a comprehensive and multifaceted scientific analysis of the health impact associated with the substitution of red meat, specifically minced beef, with cricket powder, an insect-derived ingredient. It can be considered a seminal study as it not only describes the collective exploitation of results generated in the RBA process but also presents findings addressing the research question, i.e., the outcome of a risk-benefit assessment comparing a traditional (minced beef) with a novel food (*A. domesticus* "dough"). Our findings underscore the potential viability of house cricket powder as a red meat substitute, depending on the amount of cricket powder and water incorporated in meat analogue products or meat preparations. High inclusion levels of cricket powder, in meat analogues or meat preparations may be safe, but do not necessarily represent a healthier alternative compared to beef patties, with the effectiveness of this substitution hinging on the specific recipe utilized, with sodium content having a pivotal role. Nevertheless, when the inclusion levels of cricket powder towards meat substitution are tailored, the overall health impact can be positive.

The microbiological impact also leans favourably towards the substitution, in all scenarios studied; however, its prediction might necessitate further refinement due to data gaps regarding the occurrence and concentration of potential microbiological risks associated with the cricket powder.

As a valuable resource, our study informs dietary and recipe considerations in the development of meat alternatives and relevant hybrid products. It sheds light on the potential benefits while emphasizing the areas where additional research and refinement are essential. Evidently, it is advisable to interpret the RBA results cautiously, by reporting and recognizing the inherent uncertainties, data gaps, and intrinsic variability. The study's findings, as well as the developed and implemented methodology can be a valuable tool in the field of dietary shifts for various stakeholders, including policy makers seeking informed decision-making, the food industry looking to develop new products alternative or complementary to the existing ones, and academia pursuing further in-depth research towards transforming the current agri-food system.

Disclaimer

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CRediT authorship contribution statement

Ermolaos Ververis: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Aikaterini Niforou:** Writing – review & editing, Project administration, Investigation, Data curation. **Morten Poulsen:** Data curation, Conceptualization. **Sara Monteiro Pires:** Writing – review & editing, Data curation, Conceptualization. **Michel Federighi:** Writing – review & editing, Methodology. **Evangelia Samoli:** Writing – review & editing, Supervision. **Androniki Naska:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Géraldine Boué:** Writing – review & editing, Visualization, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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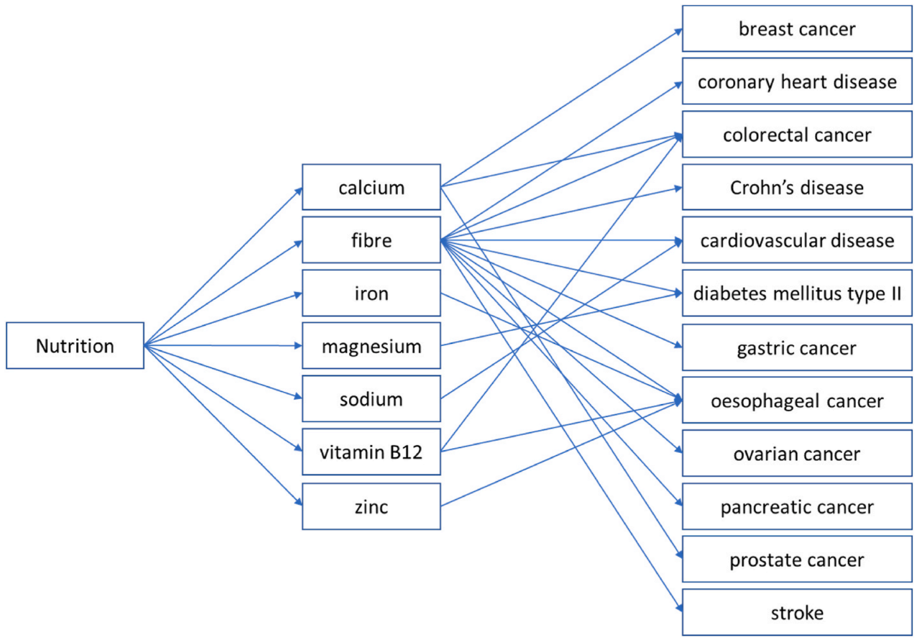
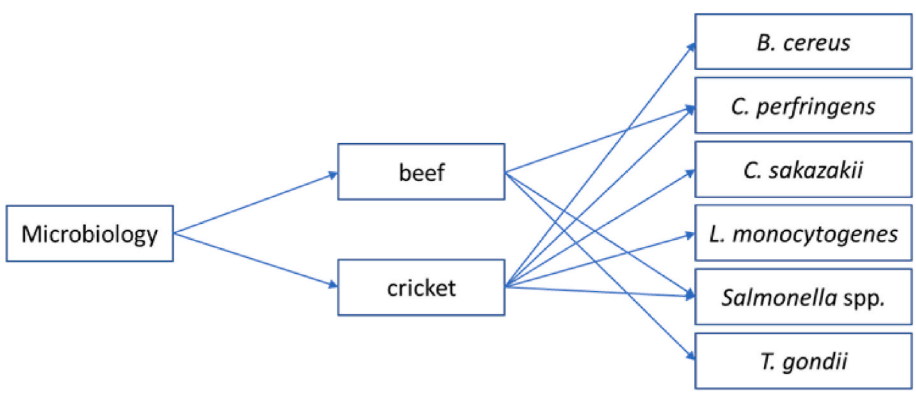
Appendix A. Health tree – Nutrition

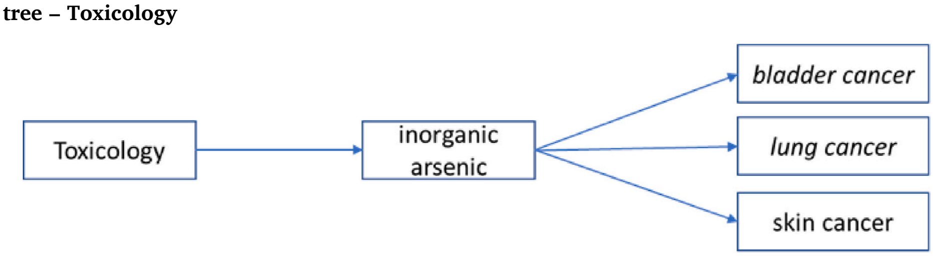


Appendix B. Health tree – Microbiology



The health effect is an infection with these microbiological agents, with the possibility to lead to the symptom(s) detailed in Table 3.

Appendix C. Health tree – Toxicology



Appendix D

(((((fiber OR fibre) AND (health*)) AND (diet* OR intak*)) AND (("2009/01/01"[Date - Publication]: "3000"[Date - Publication]))) AND (analys*[Title/Abstract])) AND (fiber [Title/Abstract] OR fibre [Title/Abstract])

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