# Levels of Rare Earth Elements in Food and Human Dietary Exposure: A Review

Neus González[1], Jose L Domingo[1]

1 Universitat Rovira I Virgili Tarragona

Funding: No specific funding was received for this work.

Potential competing interests: No potential competing interests to declare.

## Abstract

Rare earth elements (REE) are a group made up of these 17 metals: Ce, Dy, Er, Eu, Gd, Ho, La, Lu, Nd, Pr, Pm, Sc, Sm, Tb, Tm, Y and Yb. In the current century, the applications of REE have significantly increased, being used as components in high technology devices of great importance industrial and economic. However, information on human exposure to REE, as well as the potential toxic effects of these elements is still limited. In general, for metals the dietary intake is the main route of exposure for non-occupationally exposed individuals, which should be also expected for REE. The current paper was aimed at reviewing the studies conducted over the world, focused on determining the levels of REE in food samples, as well as the dietary intake of these elements. The results of most studies do not suggest potential health risks for the consumers of the analyzed freshwater and marine species of higher consumption, or derived from the intake of a number of vegetables, fruits, mushrooms, as well as other various foodstuffs (honey, tea, rice, etc.). Although the current estimated daily intakes (EDIs) of REE seem not being of concern, taking into account the expected wide use of these elements in the next years, to assess periodically the potential health risks of the dietary exposure to REE would be clearly recommendable. In fact, this is already being done with well-known toxic elements as As, Cd, Pb and Hg, among other potentially toxic metals.

**Neus González**[*], and **José L Domingo**

*Universitat Rovira i Virgili, School of Medicine, Laboratory of Toxicology and Environmental Health, 43201 Reus, Catalonia, Spain.*

[*]Correspondence to: Dr. Neus González (e-mail: nieves.gonzalez@urv.cat).

**Keywords:** Rare earth elements (REE), human exposure, foodstuffs, dietary intake, health risks.

## 1. Introduction

Rare earth elements (REE) are a group of metals, located in the middle of the periodic table, which belong to the category of emerging contaminants associated with new technologies. According to the International Union of Pure and Applied Chemistry (IUPAC), it is a group made up of 17 elements that include lanthanum (La) and the 14 lanthanides: cerium (Ce), dysprosium (Dy), erbium (Er), europium (Eu), gadolinium (Gd), holmium (Ho), lutetium (Lu), neodymium (Nd), praseodymium (Pr), promethium (Pm), samarium (Sm), terbium (Tb), thulium (Tm) and ytterbium (Yb), as well as scandium (Sc) and yttrium (Y) (USGS, 2023a, b). REE are usually divided into heavy rare earth elements (HREE): Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Sc and Y, and light rare earth elements (LREE): La, Ce, Pr, Nd, Pm, Sm and Eu. The current uses of REE are multiple and diverse. They are used in a variety of industrial applications, which include electronics, clean energy, aerospace, automotive and defense. Manufacturing permanent magnets is the single largest and most important end use for REE, accounting for 43% of demand in 2021 (USGS, 2023a, b).

In the past century, some REE were already being used in corporate and industrial research. For example, battery research led in the 1970s and 1980s to the development of the nickel–metal hydride battery, which used La and Nd. Other REE were also used as catalysts, in magnets, as well as in steel alloys. However, until recently, REE were being familiar only to a relatively small number of people, such as chemists, geologists, specialized materials scientists, and engineers. Notwithstanding, in the current century REE have gained visibility through many media. It has been mainly due to the fact that the world society has recognized the critical, specialized properties of REE, which contribute to the modern technology. It is now well known that REE have particular physical and chemical properties, such as unique magnetic and optical properties. It means that REE have a considerable number of applications that involve many aspects of the modern life. In our globalized world, another important issue related with these elements is the dominance of China in the production and supply of REE, which means an international dependence on that country for the majority of the world's REE supply (USGS, 2023a, b). Since the late 1990s, China has provided 85–95% of the world's REE. Since 2000, the uses of REE have significantly increased, being currently used as components in high technology devices, including smart phones, digital cameras, computer hard disks, fluorescent and light-emitting-diode (LED) lights, flat screen televisions, computer monitors, and electronic displays. Other applications of REE include the making of microphones, headphones, lasers, satellites, radar, and sonar. In addition, due to their luminescent properties, some REE help to make LCD screens, which go from smartphones to large television sets. Although using REE in electronics contributes a small part to the final product, this cannot function without them (Versa Electronics, 2023). Nowadays, the use of REE in electronics is essential, not having a close substitute, while their use in versatile industries makes them even more crucial.

In spite of the great and increasing interest that REE are having in our modern societies, the global environmental health effects, the potential environmental risks associated with the development of REE production, the REE toxicities, or the human health effects or REE are issues of considerable importance on which information is rather scarce (Brouziotis et al., 2022; Gwenzi et al., 2018; Oladipo et al., 2023: Pagano et al., 2015, 2019; Yin et al., 2021). For non-occupationally exposed populations, it is well established that the diet is -in general- the main source of human exposure to metals. For that reason, to know the dietary intakes of REE should be an issue of notable interest. The objective of current paper was to summarize the results reported in the scientific literature of the studies on the concentrations of REE in food, as the dietary intake when data were published. Those studies conducted by regional, national or international agencies and/or food safety authorities are not included in the present review. The databases Pubmed (https://pubmed.ncbi.nlm.nih.gov/) and Scopus (https://www.scopus.com/) were used. The terms for the search were the following: “rare earth elements”, “REE”, “food”, “dietary intake” and “human exposure”. Information on the available studies and their results are next summarized.

## 2. Levels of REE in freshwater and marine organisms

It is well known that fish, and very especially marine fish constitute an important part of the human diet. This means that its quality and its safety aspects are issues of notable interest (de Souza et al., 2021; Domingo, 2016; Pinto et al., 2022). People worldwide consume fish and seafood for their health benefits, such as vitamins and minerals, high protein, low saturated fat content, and omega fatty acids among others (Domingo, 2016; Domingo et al., 2007; Mozaffarian and Rimm, 2006; Gowda et al., 2021). In contrast to these benefits, a number of investigations have shown that fish and seafood consumption can lead to humans to be exposed to a variety of chemical contaminants, which can cause harm to the human body (Domingo et al., 2007; Mozaffarian and Rimm, 2006). In recent years, the concentrations of metals in a number of species of fish and seafood have been measured in various areas/zones around the world (González et al., 2021; Guéguen et al., 2011; Kalantzi et al., 2013; Perelló et al., 2015). However, studies regarding the concentrations of REE in freshwater and marine organisms are much more limited. These studies are here reviewed.

Table 1 summarizes the studies focused on the determination of REE in freshwater and marine organisms. Most of these studies have been conducted in China. Zhang et al. (2009) measured the concentrations of Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Er, Ho, Tm and Lu in sixty samples of marine organisms, which were collected at six sampling sites in the Shenzhen coastal region. The mean concentrations of total REE were determined. Values of 2.66 ± 2.28, 4.69 ±1.32, 0.03 ±0.03 and 0.07 ± 0.02 µg/g, for mollusk, barnacle, shrimp, and fish, respectively, were found. An enrichment of the light REE with respect to heavy REE were observed in all marine organisms. Also in China, Yang et al. (2016) carried out a survey aimed at comparing the concentrations of 14 REE in freshwater and marine fish of Shandong Province (Eastern of China). Fourteen REE (Pr, Sm, Lu, Nd, Gd, Dy, Nd, Ce, Ho, Tb, Er, Tm, Yb and Eu) were analyzed in muscle samples of four freshwater fish and six marine fish obtained from local markets and supermarkets within 17 cities of the Shandong Province. The selected fish species were the most commonly consumed by the Shandong residents. It was found that freshwater fish had a relatively higher ΣREE than marine fish (34.0-37.9 µg/kg wet weight vs. 12.7-37.6 µg/kg ww). The assessment of human health risks indicated that fish would mean little health risks derived from exposure to REE through fish consumption. On the other hand, in order to assess the potential impacts of the REE industry, Ma et al. (2019) collected samples of water and suspended particles in the Pearl River Delta (China), as well as oysters of the same place. The concentrations of the following elements were analyzed in all samples: La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu. The ΣREE concentrations in the Pearl River Delta oysters ranged between 1.8-9.1 and 0.9–2.6 µg/g for samples collected in December 2016 and June 2017, respectively. It was concluded that in the Pearl River Delta, the dominant REE uptake pathway in oysters was derived from particles. In turn, in the Shandong Province of China, Jiao and co-workers (2021) determined the levels of 14 REE (La, Ce, Nd, Pr, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu) in 120 commercial mantis shrimp (*O. Oratoria)* samples, which were collected from the coast of three sites of Shandong Peninsula. The mean concentration of ΣREE was 25.1 ng/g (range 9.04-75.1 ng/g). The levels of REE found by Jiao et al. (2021) were similar to those previously detected for marine fish: 12.7 to 37.6 ng/g by Yang et al. (2016), but lower than those found for Pearl River Delta oysters (1.8 to 9.1 µg/g) by Ma et al. (2019). The mean concentrations of the 14 REE in *O. oratoria* followed this decreasing order: La > Ce > Nd > Pr > Gd > Sm > Dy > Er > Yb > Eu > Tb > Ho > Tm > Lu. Recently, Wang et al. (2022) performed a survey aimed at determining the REE concentrations in 14 marine wild fish species from the northern coastal region of the South China Sea, as well as to characterize the distribution patterns and to assess human health risks of 15 REE (Y, La, Ce, Nd, Pr, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu). The concentrations of total rare earth elements (∑REE) ranged between 1.02 and 178.55 µg/kg, with a mean concentration of 27.14 µg/kg. The highest average value of ∑REE was found in *Apogon quadrifasciatus*, while the lowest levels corresponded to *Ariomma indica*. The estimated daily intakes (EDI) of REE through fish consumption were significantly lower than the recommended EDI limit. It clearly indicated that human exposure to REE through fish consumption of that area would be negligible.

**Table 1.** A summary of levels of REE in freshwater and marine species

| Region/country | Analyzed samples | Analyzed REE | Mean values and/or ranges | Remarks | Reference |
|---|---|---|---|---|---|
| **Shenzen coastal region, China** | mollusk, barnacle, shrimp, fish | 14 | ∑REE: 2.26, 4.69, 0.03 and 0.07 µg/g, in mollusk, barnacle, shrimp and fish, respectively | Higher levels of LREE than HREE | Zhang et al. (2009) |
| **Shandong Province, China** | freshwater (4) and marine (6) species | 14 | ∑REE: 34.0-37.9 µg/kg (freshwater species); 12.7-37.6 µg/kg (marine species) | No health risks derived from fish consumption | Yang et al. (2016) |
| **Pearl River Delta, China** | oysters | 14 | ∑REE: 1.8-9.1 µg/g (2016 sampling); 0.9-2.6 µg/g (2017 sampling) | No specific remarks | Ma et al. (2019) |
| **Shandong peninsula, China** | shrimps | 14 | ∑REE. 25.1 (9.04-75.1) µg/kg | La and Ce showed the highest levels | Jiao et al. (2021) |
| **Northern region of the South China Sea, China** | 14 marine wild fish species | 15 | ∑REE: 27.14 (1.02-178.55) µg/kg | The highest levels of ∑REE were found in *Apogon quadrifascatius* | Wang et al. (2022) |
| **Northwestern Mediterranean Sea, Italy** | Fish, mussels, oysters | La and Ce | Fish levels < LOD for La and Ce; mussels, 37 and 65 µg/kg, for La and Ce; oysters, 12 and 20 µg/kg, for La and Ce | No specific remarks | Squadrone et al. (2016) |
| **Northwestern Mediterranean Sea, Italy (3 sites)** | Brown, green and red seaweeds | 16 | ∑REE: 7.9, 8.5 and 22, for the different 3 sampling sites | No specific remarks | Squadrone et al. (2017) |
| **Ligurian Sea, Italy** | fish, bivalves, seaweeds and zooplankton | 16 | ∑REE: fish (0.21 mg/kg); bivalves (0.16 mg/kg; seaweeds (12 mg/kg) and zooplankton (0.12 mg/kg) | A periodical monitoring of the REE levels in fish and bivalves was recommended | Squadrone et al. (2019) |
| **Italian aquarium** | Spotted dogfish (samples of blood, liver, muscle and kidney | 16 | ∑REE: 4.1, 30, 15 and 13 µg/kg, for blood, liver, muscle and kidney | No specific remarks | Squadrone et al. (2022) |
| **Tokyo Bay, Japan** | 5 species of bivalves (samples of shells and soft tissues) | 14 | The individual concentrations of the 14 analyzed REE in shells and soft tissues are all reported in the original paper | REE levels in soft tissues were higher than those found in shells | Akagi and Edanami (2017) |
| **Six sampling areas in** | 12 freshwater fish | | ∑REE: 243 µg/kg (dry weight) (14-3000 | The highest ∑REE levels were | Mayfield and |

| | | | | | |
|---|---|---|---|---|---|
| **the state of Washington, USA** | species | 16 | µg/kg dw) | found in benthic feeding species of fish | Fairbrother (2015) |
| **14 Canadian lakes** | abiotic and food web components | 15 | Results are available in the original paper | The ∑REE levels in benthic invertebrates was 1000 times higher than those found in fish muscles | Aymot et al. (2017) |
| **31 sampling stations along the French shoreline, France** | mussels and oysters | 14 | ∑REE: 0.18-4.05 µg/g for mussels and 0.21-10.94 µg/g for oysters | The highest concentrations (for oysters) were found in the Gironde estuary | Briant et al. (2021) |
| **Gdansk Bay, Poland and North-East Atlantic, Spain** | Baltic herring and sardines | 17 | ∑REE; samples of muscles: 76 µg/kg for herring and 191 µg/kg for sardine | No specific remarks | Reindl and Falkowska, (2021) |
| **Six locations of the Portuguese coast, Portugal** | mussels | 15 | ∑LREE: 288-2160 µg/kg<br>∑HREE: 54-230 µg/kg | No specific remarks | Figueiredo et al. (2022) |
| **Black Sea, Crimea** | mussels | 16 | ∑REE: 710 µg/kg (dw) | In soft tissue, La and Ce, followed by Nd, Sc and Gd were the predominant REE | Chelyadina et al. (2023) |
| **Subaé River, Todos os Santos Bay, Brazil** | samples of food web (fish, shellfish, phyto- and zooplankton | 15 | ∑REE: 6.01, 1.22 and 0.059 mg/kg for bivalves, crustacean and fish | The lowest REE contents were found in fish muscle | Santos et al. (2023) |
| **Southern Caspian Sea, Iran** | Golden grey mullet | 16 | ∑REE: 14.5 µg/g | The relationship between ∑HREE and ∑LREE was 1.53 | Bakhshalizadeh et al. (2023) |

Italy is another country in which various studies on this same topic have been also performed. Most available investigations regarding the presence of REE in marine species have been conducted in the Istituto Zooprofilattico Sperimentale del Piemonte, Liguria e Valle d'Aosta, Turin. Squadrone et al. (2016) determined the concentrations of 21 trace elements in fish (*Dicentrarchus labrax*), mussels and oysters, which were collected from aquaculture marine ecosystems of the northwestern Mediterranean Sea. Among these 21 elements, the REE Ce and La were included. Neither La, nor Ce, could be detected in fish, while their levels -although rather low- were higher in mussels, Ce (0.065 mg/kg ww) and La (0.037 mg/kg ww) than in oysters, Ce (0.020 mg/kg ww) and La (0.012 mg/kg ww). A subsequent investigation of the same research group (Squadrone et al., 2017) was aimed at identifying patterns and fractionations of REE, as well as to verify the potential use of REE as pollution tracers. The concentrations of La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Yb, Tm, Lu, Y and S were measured in various species (brown, green, red) of marine seaweeds collected at 3 different sites at the northwestern Mediterranean Sea. The ΣREE (mg/kg dry weight) were 22, 8.5 and 7.9, at sites S1, S2 and S3, respectively. Seaweeds showed to be a useful tool for biomonitoring REE, since they may concentrate REE at higher levels than seawater. Squadrone et al. (2019) also measured the concentrations of La, Ce, Nd, Sm, Eu, Gd, Dy, Er, Yb and Lu, in 70 samples of different matrices of marine origin collected from the Ligurian Sea (northwestern Mediterranean Sea). Fish (mullet, redfish, mackerel, and hake) and bivalves (mussels, clams, and oysters) samples were analyzed, while the levels of the REE were also determined in samples of seaweeds (Chlorophyta, Ochrophyta and Rhodophyta) and zooplankton ($n = 12$) collected from the Ligurian Sea. The highest ΣREE were found in seaweed (mean: 12 mg/kg), followed by fish (0.21 mg/kg), bivalves (0.16 mg/kg) and zooplankton (0.12 mg/kg), being the ΣREE concentration in seaweed significantly higher than the levels detected in fish, bivalves and zooplankton. Taking into account that fish and bivalves are potential sources of human dietary exposure to REE, the authors suggested a periodical monitoring of their concentrations in order to prevent potential harmful cumulative effects in humans. Related with the levels of REE in fish, Squadrone et al. (2022) also measured the concentrations of 40 elements (24 trace elements and 16 REE) in blood, liver, kidney and muscle of spotted dogfish (*Scyliorhinus stellaris*) reared in an Italian aquarium. Although this fish is only of moderate commercial fisheries relevance, human consumption is not especially rare in the Mediterranean. The mean ΣREE were 4.1±0.51, 30±1.6, 15±2.0 and 13±1.3 μg/kg in samples of blood, liver, muscle and kidney, respectively, being Sc the most abundant REE.

In Japan, Akagi and Edanami (2017) determined the concentrations of 14 REE (La, Ce, Nd, Pr, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu) in five species of bivalves (Japanese littleneck, blue mussel, trough shell, Stimpson's quahog, and Japanese dosinia), species which were collected from three different sites in Tokyo Bay, being samples of shells and soft tissues specifically analyzed. Although there were considerable differences among the 14 REE analyzed, it was observed that the REE levels in soft tissues were higher (by an order of magnitude) than those found in shells. In turn, in USA, Mayfield and Fairbrother (2015) carried out a study focused on characterizing the concentrations of 16 REE (Sc, Y, La, Ce, Nd, Pr, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu) within several freshwater fish species from a large reservoir (six collection areas) that lies within the State of Washington. REE concentrations were measured in tissues and their relationships with tissue type, size, and trophic group were examined. Samples of the following fish species were included: burbot, kokanee, longnose sucker, largescale sucker, lake whitefish, mountain whitefish, rainbow trout, smallmouth bass, sculpin and walleye. Total concentrations of REE (ΣREE) ranged from 0.014 to 3.0 mg/kg dw and averaged 0.243 mg/kg dw. It was observed that benthic feeding species, which are exposed to sediments, showed higher levels of REE than pelagic omnivorous or piscivorous species. On the other hand, Amyot et al. (2017) conducted a study whose main objective was to characterize the background levels and trophic transfer of REE in natural environments of North America. In order to assess the natural ecosystem fate of 15 REE (Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu), abiotic and food web components were sampled in 14 Canadian temperate lakes, which were unaffected by mines. It was found that individual levels of REE and ΣREE were strongly related with each other throughout different components of lake food webs. The ΣREE were 32, 40 and 275 times higher in whole body than in muscles for brown bullhead, creek chub, and white sucker, respectively. In turn, ΣREE levels in benthic invertebrates were approximately 1000 times higher than those detected in fish muscle (median of 20 nmol/g vs. 0.02 nmol/g, respectively). Nonpredatory benthic invertebrates (mean ± SD, 60 ± 69 nmol/g) had significantly higher ΣREE than predatory benthic invertebrates (16 ± 14 nmol/g) and zooplankton (13 ± 12 nmol/g). It was concluded that the low concentrations of REE observed in freshwater fish muscle, compared to their potential invertebrate prey, would suggest that fish fillet consumption is unlikely to mean a significant source of human exposure to REE in those areas not affected by mining activities of REE. In France, Briant et al. (2021) determined the concentrations of 14 REE (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu) in mussels (*Mytilus edulis, Mytilus galloprovincialis*) and oysters (*Crassostrea gigas*) soft tissues, collected along the French shoreline (31 sampling stations). ∑REE concentrations in bivalves varied among the sampling stations, with a range between 0.18 and 10.94 μg/g. The ∑REE concentrations in mussels and oysters were 0.18–4.05 μg/g, and 0.21–10.94 μg/g, respectively. The highest concentrations were found in the Gironde estuary, with the ∑REE in oysters being up to 10.94 μg/g dw. On the other hand, Reindl and Falkowska (2021) determined the concentrations of REE in muscles of pelagic fish (Baltic herring (*Clupea harengus*) and sardines (*Sardina pilchardus*) from two European regions: the Gdansk

Bay (South Baltic Sea) and the Iberian Peninsula (North-East Atlantic). These marine species, in various forms (fresh, frozen, processed), are available in the European market. The levels of the examined REE (lanthanides: light REE (LREE, La–Eu) and heavy REE (HREE, Gd–Lu and Y) and Sc) in the ova and seminal fluid were also analyzed. REE were detected in the muscles of the Baltic herring ( ∑ REE = 0.076 ± 0.047 mg/kg) and the sardine ( ∑ REE = 0.191 ± 0.163 mg/kg), being the heavy REE the dominant in both species. For Baltic herring and sardine, the ∑ REE in muscles were lower than those observed in ova and seminal fluid. In Portugal, Figueiredo et al. (2022) measured the levels of REE in mussels (*Mytilus galloprovincialis)* from six locations of the Portuguese coast. The analyzed REE were divided into light rare earth elements (LREE: La, Ce, Pr, Nd, Pm, Sm and Eu) and heavy rare earth elements (HREE: Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu). The concentration of ∑ LREE varied between 288 ng/g in Aljezur (the southernmost point on the Portuguese coast) during autumn, and 2160 ng/g in Porto Brandão (south bank of the Tagus estuary) during spring, while ∑ HREE ranged from 54 ng/g in Aljezur during autumn, and up to 230 ng/g in Porto Brandão during spring. In Crimea, Black Sea, Chelyadina et al. (2023) measured in samples of mussels (*Mytilus galloprovincialis)* the concentrations of 16 REE (all the 17 REE excepting Pm). The levels of REE were analyzed in soft tissues, byssus, and shell liquor of the mussels collected in three sampling locations of Crimea. ΣREE in mussels were on average 0.71 mg/kg dw. In soft tissue and byssus, La and Ce were the dominant elements at the 3 sampling stations, followed by Nd, Sc and Gd. In turn, in shell liquor, the dominant REE were Tb, Gd and Nd, while La was also among the dominant elements at Stations 2 and 3. According to the values of target hazard quotients based on two estimates of the threshold oral reference dose, in terms of REE intake, the authors concluded that mussel consumption should not mean dietary risks to human health. In Brazil, Santos et al. (2023) recently studied the fate of REE, their incorporation in biota, and transfer along a food web of the Subaé River, which is one of the main tributaries of the Todos os Santos Bay (northeastern of the country), a heavily contaminated estuary. The levels of 15 REE (Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu) were determined in sediments, suspended particulate matter, as well as important biota (shellfish and fish) for the local community. The ∑ REE in phytoplankton and zooplankton were 45.7 and 68.5 mg/kg, respectively, values considerably lower than those found in bivalves, crustaceans and fish: 6.01, 1.22 and 0.059 mg/kg, respectively. The lowest values corresponded to fish muscle. It was concluded that although seafood consumption would be unlikely to be an important source of exposure to REE for humans, taking into account that fish muscle is the main tissue consumed, the levels of REE in fish and seafood should be periodically monitored. In Iran, also recently, Bakhshalizadeh et al. (2023) measured the concentrations of 16 REE (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Sc and Y) in 20 golden grey mullets caught in the south of the Caspian Sea (Bandar Anzali Coast). The levels were compared with the normal values of these elements in the earth's crust. The ∑ REE was 14,550 pg/g, with a relationship between ∑ HREE and ∑ LREE of 1.53. Although all mullet samples contained much lower levels of REE than the concentrations reported on the earth's surface, it should be highlighted that Tb, one of the scarcest elements in the world, was found to be the third most abundant REE. It would suggest that the notable Tb presence was the result of rather recent anthropogenic activities.

## 3. Levels of REE in vegetables and fruits

Table 2 summarizes the studies focused on the determination of REE in vegetables and fruits. In Hetian Town (Fujian Province, China), Li et al. (2013) conducted a study aimed at measuring the levels of REE in soil and vegetables collected from farms (6 sampling sites) near mining sites of that place. The health risks of human REE exposure due to vegetable consumption were evaluated. The levels of 15 REE (all the 17 REE, excluding Sc and Pr) were determined in samples of the following vegetables: Chinese white cabbage, taro, Chinese radish, water spinach, lettuce, long bean, pakchoi, and eggplant. The ∑REE in vegetables ranged between 0.06 and 64.42 µg/g dw (average: 3.58 µg/g dw). The mean contents of REE in vegetables collected in the vicinity of the mining sites were significantly higher than those found in samples collected in a control site, which indicated that REE from rare earth mining was an evident source of REE pollution. The daily intakes of the 8 analyzed vegetables decreased in the following order: taro > water spinach > lettuce > parkchoi > long bean > eggplant > white radish> Chinese cabbage. According to the authors of that study, the consumption of these vegetables should not result in daily intakes of REE that could mean health risks (safe values: 100–110 µg/kg/day) for adults and children. In a subsequent Chinese study, Zhuang et al. (2017a) measured the concentrations of REE in 301 samples of a number of vegetables (edible parts of Chinese cabbage, scallion, white gourd, long bean, eggplant, tomato, potato, towel gourd, pumpkin, red pepper, radish and carrot), which were collected from 10 sampling sites (5 from a mining area in Shandong and 5 control sites) in Weishan County. The health risks of human exposure to REE through vegetable consumption were also assessed. Fourteen REE (Sc, Pr and Y were excluded) were analyzed. The average concentration of REE was 66.47 µg/kg, being 94.08 and 38.67 µg/kg the average levels found for vegetables collected from mining and control areas, respectively. The difference was significant. La, Ce, Pr, and Nd were the most abundant REE, which accounted for over 91% of total REE in both mining and control sampling sites. On the other hand, the levels of ∑REE in the analyzed vegetables decreased in this order: leaf vegetable > taproot vegetable > alliaceous vegetable > bean > solanaceous vegetable > tuberous root vegetable > gourd vegetable. The EDIs of the total REE were 0.69 and 0.28 µg/kg/day, respectively, for samples collected in the mining and control areas. These values were significantly lower than the established EDI (70 µg/kg/day). Although those EDIs would not mean health risks in adults, the authors recommended to pay attention to the potential risks in children derived of a continuous exposure to low levels of REE. Also in China (Xinfeng County, Jiangxi province), Cheng et al. (2015) investigated the transfer characteristics of 15 REE (Ce, La, Nd, Y, Pr, Gd, Sm, Dy, Er, Yb, Eu, Ho, Tb, Tm and Lu) from soils to navel oranges. The effects of these REE on the internal quality of that fruit were also examined. The concentration of REE in navel orange pulp was low, ranging between 0.106 and 0.829 mg/kg dw (average: 0.341 mg/kg dw). The LREE accounted for approximately 84% of the total contents of REE, with Ce being the predominant element. The REE level in navel orange pulp was 14 times lower than the food safety limit set in China (MHPRC, 2005). Even when total soil REE level was as high as 1038 mg/kg, the consumption of navel oranges was still safe for humans. In a more recent study on the same topic, Shi et al. (2022) determined the levels of REE in fruits (288 samples of pome fruits, drupes, citrus, melon fruits, tropical and subtropical fruits, berries, and small fruits) and vegetables (942 samples of solanaceous, brassica, melon vegetables, stem vegetables, root and tuber vegetables, bulb vegetables, fresh legumes and leafy vegetables). Samples were collected near mining areas of China (Bayan Obo in Inner Mongolia, Weishan in Shandong, Maoming in Guangdong and Longnan in Jiangxi) and in control sampling points. The levels of 16 REE (Sc, Y, La, Ce, Nd, Pr, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu) in fruits were 12.90 and 11.89 µg/kg in the mining and control areas, respectively. In turn, the levels of REE in vegetables were 92.90 and 62.38 µg/kg in mining and control areas, respectively. Regarding the EDIs, these were in the ranges 0.02–0.06 and 0.53–1.22 µg/kg/day for fruit and vegetables, respectively. These daily intakes were considerably lower than the regular allowable daily intake (60.4 µg/kg body weight) for all gender/age groups of consumers.

**Table 2.** A summary of available information on the levels of REE in fruits and vegetables

| Region/country | Vegetables/fruits | Analyzed REE | Mean values and/or range | Remarks | Reference |
|---|---|---|---|---|---|
| **Fujian Province, China** | 8 species of local vegetables | 15 | ∑REE, mean: 3.58 µg/g (dw) (0.06-64.42 µg/g) | The daily intake of the analyzed vegetables was safe | Li et al. (2013) |
| **Weishan County, China** | 12 species of vegetables from 10 sampling sites | 14 | ∑REE, mean: 94.08 and 38.67 µg/kg in vegetables collected in mining and control areas, respectively | La, Ce, Pr and Nd accounted for over 91% of total REE in mining and control areas | Zhuang et al. (2017) |
| **Xinfeng County, Jiangxi Province, China** | pulp of navel oranges | 15 | ∑REE, 0.341 µg/g (dw) (0.106-0.829 µg/g) | LREE accounted for 84% of the total content of REE | Cheng et al. (2015) |
| **Four mining points (Inner Mongolia, Shandong, Guangdong and Jiangxi), China** | 228 samples of various fruits and 942 samples of several species of vegetables | 16 | ∑REE, fruits: 12.90 and 11.89 µg/kg in fruits collected in mining and control areas. In vegetables, 92.90 and 62.38 µg/kg | EDIs were in the ranges 0.02-0.06 and 0.53-1.22 µg/kg/day, for fruits and vegetables, respectively | Shi et al. (2022) |
| **La Palma, Canary Islands, Spain** | bananas collected from an area affected by a volcanic eruption, and control sites | 17 | ∑REE, 61.4 (peel) and 14.2 (flesh) ng/g. In control sites; 16.2 (peel) and 5.7 (flesh) ng/g | The intake of REE from consumption of bananas would not exceed 5% of the tolerable daily intake for any of the REE | Rodriguez-Hernández et al. (2022) |

On the other hand, following a volcanic eruption that occurred in 2012 in the island of La Palma (Canary Islands, Spain), the concentrations of 50 elements were determined in bananas obtained from the affected area (Rodriguez-Hernández et al., 2022). The REE: Ce, Dy, Er, Eu, Gd, Ho, La, Lu, Nd, Pm, Pr, Sc, Sm, Tb, Tm, Y and Yb were included in the survey. The median values of ∑REE in peel and flesh samples of the fruits collected in the volcano area were 61.4 and 14.2 ng/g, respectively, being 16.2 and 5.7 ng/g the values found to the bananas in the control area. For both peel and for flesh, the differences were significant. Anyhow, these higher levels should not mean a real risk for the consumers. Even the consumption of bananas from the volcano area would be of little relevance in terms of human health. On average, the intake of REE from consumption of bananas would not exceed 5% of the tolerable daily intake of any of the REE. On the other hand, in order to gather information on the occurrence of REE in the daily diet of adults and children, Doulgeridou et al. (2020) published a review on potentially toxic REE, plus thallium and tellurium, in plant-based foods (edible plants). The studies reviewed in that paper have been also included in the current review.

## 4. Mushrooms

It is known that mushrooms are certainly effective to bioconcentrate different chemical elements -including trace elements and REE- from substrate, in which mycelium lives to developed fruiting bodies. In the scientific literature, there are a number of available studies focused on monitoring REE in edible mushroom species. Most of these investigations have been performed in Poland, and more specifically in the Laboratory of Environmental Chemistry & Ecotoxicology, Gdańsk

University. The results are next summarized. Falandysz et al. (2017a) measured the concentrations of La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Sc and Y in composite samples of caps and a whole fruiting bodies of the mushroom *Macrolepiota procera,* whose samples were collected across Poland. The total concentrations of ΣREE in caps (13 sites) and whole fruiting bodies (3 sites) were 0.50 and 0.75 mg/kg dry biomass (db), respectively. Cerium was the most abundant REE, with a mean value in the caps at 0.18 ± 0.09 mg/kg db (range: 0.030-0.34 mg/kg db). In contrast, the lowest levels (0.0011 mg/kg db) corresponded to Lu and Tm. According to the authors, the levels of REE found in *M. Procera* indicated that eating a tasty cap of this mushroom should not mean health risks for the consumers. In another study of the same research group, Falandysz et al. (2017b) investigated the multi-elemental composition and associations between 32 trace elements and 16 REE (the same elements analyzed in the study by Falandysz et al. (2017a)) accumulated in fruiting bodies (caps and stipes) of samples collected at 16 sites from northern and central regions of Poland. Among the 48 elements analyzed, the highest levels corresponded to Cd, Hg and Pb found in edible caps of the fruiting bodies. With respect to REE, as in the survey by Falandysz et al. (2017a), the concentrations of REE detected in *M. Procera* should not mean health risks for the consumers. More recently, Falandysz (2021) carried out a survey focused on extending the data on the levels of 30 metals in samples of the king bolete mushroom, *Boletus edulis* (fruiting bodies). The ΣREE (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu) was determined. For the Σ14 REE, the median was 0.31 mg/kg dw (range: 0.074-1.8 mg/kg dw). For all the elements analyzed in that survey, including the 14 analyzed 14 REE, their concentrations -even those of the most notoriously toxic metallic elements- in *B. edulis* were considered harmless. In a subsequent survey, Falandysz et al. (2022) determined the concentrations of the REE: La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Sc and Y in parts of the fruiting bodies of *B. edulis* (14 composite samples derived from 261 whole fruiting bodies). Samples were collected from geographically distant locations of Poland. Cerium was the most abundant REE, followed by La and Nd, with median levels of 95, 51 and 32 µg/kg, respectively. The median REE concentrations in the caps, stipes, and whole fruiting bodies followed this order: LREE > MREE > HREE. The median levels (µg/kg dw) for these subgroups were 121.4, 12.8 and 5.6 µg/kg dw in the caps, 218, 19.1 and 9.2 µg/kg dw in the stipes, and 187.7, 17.6 and 8.7 µg/kg dw for the whole fruiting bodies. As for other mushrooms, it was concluded that consumption of *B. edulis*, should not mean any known toxicological risk, even for high-level consumers. On the other hand, Medyk and Falandysz (2022) conducted a study focused on exploring the bioconcentration potential and status of La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu and Y in samples of eight different species of wild mushrooms and forest topsoil (0–10 cm layer) collected from 3 countries: Poland, Belarus and China. The ΣREE levels in mushrooms ranged from 15.8 µg/kg dw in caps of *I. badia* and 443 µg/kg dw in *C. cibarius*. It was observed that the levels varied between species, with some differences detected also in REE concentration from the same species collected at distantly located sampling sites. Recently, the same research group (Medyk et al., 2023) carried out a new study whose main purpose was to characterize the presence of REE in a relatively large sample (22 composites of 2235 specimens) of *Cantharellus cibarius* collected from 22 locations across Poland. In addition, a pooled sample (153 specimens) of *C.minor* collected at Yunnan (China) was also included in that survey. The mean concentration of ΣREE (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Sc and Y) found in *C. cibarius* was 176 67 µg/kg dw, while the pooled sample of *C.minor* from Yunnan contained a higher level of ΣREE (2072 µg/kg dw) than *C.cibarius* from Poland. Anyhow, the amounts of the REE detected in *C.cibarius* mushrooms in that survey would be considered certainly low -and even negligible- from a point of view of food safety.

Other authors have also determined the levels of REE in wild (edible) mushrooms species growing in Poland. Mleczek et al. (2016) measured the concentrations of platinum group elements (PGEs) and REE in 20 mushroom species (10 above ground and 10 growing on wood). The highest levels of REE in *Suillus luteus* and *Tricholoma equestra* were 5.03 ± 0.50 and 2.18 ± 0.56 mg/kg dw, respectively, while for mushrooms growing on wood bodies it was 4.19 ± 0.78 mg/kg dw in *Ganoderma applanatum* fruiting. The mean concentrations of REE were 1.39 ± 1.21 and 1.61 ± 0.97 mg/kg dw, respectively, in above-ground species and species growing on wood. In turn, Siwulski et al. (2020) examined the trends of the content of REE (La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, Ho, Er, Tm, Yb, Lu, Sc and Y) in four edible mushroom species: *Boletus edulis*, *Imleria badia, Leccinum scabrum* and *Macrolepiota procera,* which were collected in forests of Poland between 1974 and 2019. The ∑REE (mean and range in mg/kg dw) in fruit bodies of the examined species were: 2.00 (0.228–4.06), 2.43 (0.879–4.23), 0.607 (0.343–1.71) and 0.593 (0.203–1.46) for *B.edulis*, *I.badia, L.scabrum* and *M.procera, respectively.* It was found that the REE content in the examined mushrooms increased between 1990 and 2010, decreasing later, most apparently in *I. badia*.

In Greece, Koutrotsios et al. (2018) measured the concentration of 16 REE (Ce, Dy, Er, Eu, Gd, Ho, La, Lu, Nd, Pr, Sc, Sm, Tb, Tm, Y and Yb) in various mushroom production substrates, as well as in the edible fruit-bodies of the species *C. cylindracea* and *P.ostreatus*. As in other studies above reviewed, the REE detected at higher levels in fruit-bodies was Ce (31–81 and 33–75 g/kg for *C.cylindracea* and *P. Ostreatus* respectively), followed by La (13–42 and 15–39 g/kg), Nd (3.1–53 and 3.4–13 g/kg), and Sc (15–27 and 3.4–13 g/kg). It was in agreement with the results observed from analysis of substrates. Regarding health risks, the EDIs of REE were estimated to be in the ranges 0.034-0.098 and 046–0.081 g/kg/day for *C.cylindracea* and *P.ostreatus,* respectively. The results suggested that consumption of cultivated mushrooms at the REE concentrations found (even on substrates with a high content of REE), would not be potentially harmful for human health. In Serbia, Vukojevic et al. (2019) determined baseline concentrations of REE (Sc, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu and Y) in soils from two different geographical sites, an unpolluted mountain region (S1) and a forest near the city of Trstenik (S2). The accumulation in the mushroom *Macrolepiota procera* was also estimated. The median values (µg/kg) of the ∑LREE were 0.21 (S1) and 0.12 (S2), and 0.47 (S1) and 0.93 (S2), in cap and stipe samples, respectively. In turn, the median levels of the ∑HREE were 0.021 (S1) and 0.012 (S2), and 0.032 (S1) and 0.041 (S2), in cap and stipe samples, respectively. The results showed that wild *M.procera* did not have the ability to accumulate REE from either of the soils (BCF values were lower than 1). On the other hand, while preparing the current paper, an interesting critical review of REE in cultivated macrofungi has been published by Falandysz et al. (2024). These authors have concluded that a significant proportion of the previously reported data show unexplained anomalies in occurrence patterns. This might be unsuitable for assessing human health risks derived from exposure to REE, as well as to evaluate potential increasing trends of REE contamination in foodstuffs.

## 5. Other foodstuffs

Howe et al. (2005) reported the concentrations of 27 elements in samples of various food that were collected from farms and markets in central Jamaica. The following food groups were included: fruits, legumes, leafy and root vegetables, and other root crops (being potatoes the item most consumed of this group). Among the 27 analyzed elements, 5 REE (Ce, Eu, La, Sc and Sm) were included. For Ce, most food samples were below the detection limit, with the highest levels observed in "callaloo" (0.24 mg/kg) and red kidney beans (0.006 mg/kg). For the rest of analyzed REE, the concentrations were in the ranges: 0.004 (fruits)-0.061 mg/kg (vegetables leafy); 0.3 (vegetables leafy)-1.09 µg/kg (fruits); 0.4 (fruits)-3.4 µg/kg (vegetable roots), and 0.6 (fruits)-4.6 µg/kg (vegetables leafy), for La, Eu, Sc and Sm, respectively. The authors stated that it would be unlikely that dietary exposure to these 5 REE might mean public health risks. In China, Jiang et al. (2012) determined the levels of 16 REE (Sc, Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu) in samples of fresh vegetables, cereals, fresh meat, eggs, and aquatic products (mollusks, crustaceans, and marine and freshwater fish). The average contents of Dy, Ce and La were between 0.0524 and 0.0289 mg/kg (high level), while the mean levels of Sc, Y, Er, Nd, Gd and Pr were between 0.0184 and 0.0082 mg/kg (middle level). In turn, the mean concentrations of Sm, Yb, Ho, Eu, Tb, Tm and Lu were between 0.0038 and 0.0012 mg/kg. The mean concentration of total REE was 0.2060 mg/kg. In general, the 16 REE were found at low levels in all the examined foodstuffs. Also in China, Zhuang et al. (2017b) carried out a study aimed at investigating the concentrations of 14 REE (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu) in cereals of mining and control areas in Weishan County (near to a large-scale REE mining site in Shandong). The potential health risks derived of the REE exposure through cereal consumption were also assessed. The average concentration of ΣREE for the 327 analyzed samples was 55.79 g/kg, while for the samples of cereals collected from the mining and control areas, the mean concentrations were 74.22 and 47.83 g/kg, respectively. It was found that La, Ce, Pr and Nd were the most abundant REE, accounting for over 90% of the total REE for the mining area. The EDIs of the total REE were considerably lower than the allowable daily intake (70 g/kg bw).

Some data on the concentrations of REE in honeys are also available in the scientific literature. Squadrone et al. (2020a) conducted a survey focused on assessing the occurrence of a number of trace elements and 16 REE in honeys from various countries. Another objective of the study was to evaluate if the metal concentrations in honeys might be permissible for human consumption. The levels of La, Ce, Pr, Nd, Sm, Gd, Eu, Tb, Dy, Tm, Yb, Ho, Er, Lu, Y and Sc were analyzed in samples of multi-floral honeys from the Balkans (n 0), Kazakhstan (n 0), Italy (n 0), South America (n 0) and Tanzania (n ). The ΣREE in multi-floral honeys followed this decreasing order: Tanzania (65 µg/kg) taly (11 µg/kg) outh America (9.8 µg/kg) he Balkans (9.3 µg/kg) nd Kazakhstan (9.1 µg/kg). The LREE/HREE ratio ranged between 0.28 (Italy) and 2.5 (Tanzania). The same research group (Squadrone et al., 2020b) measured the concentrations of 24 trace elements and 16 REE (La, Ce, Pr, Nd, Sm, Gd, Eu, Tb, Dy, Tm, Yb, Ho, Er, Lu, Y and Sc) in monofloral and multifloral honeys from Piedmont (Northwestern Italy). The safety of the consumption of the analyzed honeys was also assessed. Ninety-one samples of acacia (n = 26), chestnut honey (n = 18), linden honey (n = 15), rhododendron honey (n = 14) and multifloral honey(n = 18) were collected and analyzed for the 16 REE. For these honeys, the ΣREE were 6.6, 12, 11, 14 and 6.0 µg/kg, respectively. The highest concentrations of REE were found in chestnut honey, while the lowest levels corresponded to acacia and rhododendron honeys. Based on the results (not only for REE, but also for trace elements) of that survey, and taking also into account the nutritional value of the analyzed honeys, their consumptions are recommended and should not mean any potential health risk. In Jordan, Tahboub et al. (2022) conducted a survey aimed at determining the concentrations of 46 elements in 18 imported samples and 12 local samples of honeys (monofloral and multifloral). Among the analyzed elements, these 15 REE were measured: Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu. The highest levels (in decreasing order) corresponded to Ce> Nd> La> Pr> Sm. The total mean of ∑REE was 145 ±157 μg/kg (range: 41–489 μg/kg), being the mean levels 203 ± 165 and 98 ± 113 μg/kg, for local and imported honey samples, respectively. For all analyzed elements, including those potentially toxic and the 15 REE, the concentrations in honeys were found to be much lower than their guideline limits, indicating the safety for human consumption. In China, Wang et al. (2020) measured the levels of 16 REE in 3011 tea samples of four types (black tea, green tea, oolong tea and dark tea), samples that were obtained in the main tea producing areas in different provinces of the country. The highest mean levels of ∑REE (mg/kg) were 2.960, 2.500, 3.870 nd 2.955 in black tea (Henan province), green tea (Shanxi province), oolong tea (Guizhou province), and dark tea (Hunan province). The tea leaves accumulated mainly light REE rather than heavy REE. In general, the highest content of REE in teas corresponded to Ce, regardless of the province of collection. The most abundant REE followed this order: Ce a c d in black and green teas, being the trend Ce c d a in oolong tea, and Ce a d c in dark tea. Recently, Kowalczyk et al. (2022) assessed the levels in teas of 16 REE (La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Y and Sc), together with Sb, Ba, B, Li, Te, Tl and V. The potential health risks of the consumption of teas were next assessed. Due to the lack of substantial information on the toxicity of most REE, the related uncertainty was considered as high. La, Ce and Y were found to constitute 60% of total REE contamination in teas, being the contribution from the rest of REE considerably lower. Based on their findings, Kowalczyk et al. (2022) concluded that exposure to REE through tea consumption should pose a negligible risk to the consumers. Even no adverse effects could be expected for high tea consumers. Recently, Imran et al. (2023) determined the levels of 16 REE (Sc, Y, La, Ce, Pr, Nd, Sm, Gd, Eu, Tb, Dy, Tm, Yb, Ho, Er and Lu) in 64 samples of rice grown in Australia and imported rice from various countries (India, Italy, Pakistan, Sri Lanka, Thailand, Vietnam and USA). The average levels of REE were 0.013–2.974, 0.012–3.113 and 0.009–0.919 μg/kg in Australian, Thailand and Vietnamese rice samples, respectively. The highest average levels of REE corresponded to rice samples from Pakistan (0.299–128.2 μg/kg), India (0.063–20.574 μg/kg) and Sri Lanka (0.022–11.522 μg/kg). Individually, the concentrations of light REE (Sc, La, Ce, Nd) were higher than those of heavy REE. According to the authors, the differences detected among samples of the selected countries could be due to different agricultural practices, geological and topographical variation, as well as the use of fertilizers with different REE composition. The health risks for the Australian population due to rice consumption were not assessed in that study. On the other hand, the bioaccumulation of the REE Sc, Ce and Eu (plus Hf and Ta, as well as other trace elements) was evaluated in oats in barley grown in soils of Russia, soils with different characteristics and level of contamination (Shtangeeva, 2022). Soil samples for that survey were collected at 3 different sites (S1, S2 and S3) in St. Petersburg. The plants were grown in these soils, which differed in texture, pH, and concentrations of exchangeable cations, and important, also in the levels of contamination. In the roots, the levels of Sc were in the ranges 0.11-0.37 mg/kg and 0.15-0.23 mg/kg in oats and barley, respectively, being the levels of Ce 1.9-3.8 mg/kg and 1.7-1.8 mg/kg in samples of oats and barley, respectively. In turn, the levels of Eu showed these ranges: 0.04-0.08 mg/kg in oats and 0.009-0.017 mg/kg in barley. The values found in roots were significantly higher than those detected in the leaves of the oats and barley. In a previous study conducted by Squadrone et al. (2019) in Italy, the levels of La, Ce, Nd, Sm, Eu, Gd, Dy, Er, Yb and Lu were measured in samples of plant feed, fruits, honey and wildlife livers. Specifically, 30 samples of plant feed (bran, oat, forage, wheat and barley), 30 samples of fruits (apples, strawberries, peaches and apricots) and 30 samples of honeys were collected in the Piedmont Region (Northwestern Italy). Additionally, 15 liver samples of wild species (boar, roe deer, deer, been sparrow hawk, tawny owl and crow) were collected in that region, from animals that were found dead by local veterinarian services. The highest means of ΣREE were detected in plant feed (mean: 1.8 mg/kg), followed by wildlife livers (0.043 mg/kg), fruits (0.0088 mg/kg), and honeys (0.0078 mg/kg). Among all the analyzed samples, fruits and honeys showed very low REE levels, while plant feed, -mainly represented by raw cereals- reached the highest REE levels, which might mean a major source of exposure. Recently, Kollander et al. (2023) reported the concentrations of 74 elements in traditional and new food varieties in the Swedish market. Fourteen REE (Ce, Dy, Er, Eu, Gd, Ho, La, Lu, Nd, Pr, Sm, Tb, Tm and Yb) were analyzed in that survey. The food groups included cereal products, seeds, potato products, vegetables, algae and algae products, as well as “new” food items (vegetarian protein products, quinoa, teff flour, chia and psyllium seeds). That study provided levels of elements that are not routinely analyzed in foods, and not requested within the EFSA call for data. Because of the enormous quantity of data contained in that survey, we have not here reported the specific concentrations for all the analyzed elements including the 14 REE. For a detailed and extensive information, we refer to Kollander et al. (2023). Recently, Henriquez-Hernández et al. (2023) determined the content of 38 elements in 159 samples of ready-to-eat baby food sold in Spain. These elements included 17 REE (La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Sc and Y). The median concentrations (ng/g fresh product) of ΣREE in ready-to-eat puree for babies were 7.3 (fruit purees), 6.2 (chicken purees), 9.6 (fish purees) and 10.1 (beef purees) in major name brands. In store brands, the median levels were 5.9 (fruit purees), 12.1 (chicken purees), 8.0 (fish purees) and 16.1 (beef purees). For risk assessment, the analysis was carried out for two different exposure scenarios: a) children, who were at the average consumption of the foods considered, and b) children, who were at the 97.5th percentile of consumption. In the first scenario, no risks associated with the intake of REE were found, while in the second scenario, the maximum tolerable intake (according to data reported by other authors) was reached.

## 6. Human dietary exposure to REE and risk assessment

In recent decades, due to the widespread use of REE in electronics industry, lasers, advanced materials, superconductors and medicine, among many others, the demand for REE has dramatically increased. Consequently, it has mean an environmental release of these elements, which has been/is being clearly detected in recent years (Gwenzi et al., 2018; Pagano et al., 2019; Pereira et al., 2022; Zapp et al., 2022) Consequently, human exposure to REE, which could have been more or less irrelevant until recent decades, in a few years could be of concern (Oladipo et al., 2023; Yin et al., 2021). For non-occupationally exposed individuals, the diet is the most important route of exposure to metals (Bocio et al., 2005; González et al., 2021). In relation specifically to REE, in recent years, some human dietary exposure to these elements have been conducted in China. The results are now available in the scientific literature. Dai et al. (2022) determined the exposure to REE in the Chinese resident diet through a market-based study. Samples of cereals, beans, potatoes, leafy vegetables, root vegetables, melon vegetables, legumes, edible fungi, pork, beef, mutton, poultry, eggs, pure milk, mixed animal fats, fish, shrimp, shellfish and cephalopods, were collected from 33 cities of China, and the concentrations of 16 REE (La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu and Y) were measured. The average concentration of ΣREE was 64.95 μg/kg ww, with a range between 2.12 and 809.68 μg/kg ww in the different kinds of samples. The highest ΣREE (605.46 μg/kg) corresponded to shellfish samples, while the lowest ΣREE level was detected in milk samples (18.43 μg/kg). The EDIs of REE were estimated for 5 Chinese regions of China, being 0.54 μg/kg/day the average intake of REE via food consumption. The maximum EDI was found in Midland (0.90 μg/kg/day). The highest health risk of dietary exposure to REE corresponded to cereals intake, with a contribution to the total EDI -in the 5 regions- between 45.44% and 69.78%. It was followed by vegetable and aquatic animals' intake. In contrast, the risks due to the consumption of milk, eggs, and beans were relatively lower, contributing approximately with a 10% of the total EDI. In general, the health risks of REE detected in that study were considered as acceptable. A similar survey was also conducted in China by Yang et al. (2022). That study was aimed at investigating the levels and patterns of 16 REE (Pm was not included) in a number of food samples of 11 main categories, obtained in 31 Provinces of China, as well as to assess the dietary intake of REE by the Chinese population. The mean concentrations of Ce, La, Y and Nd (0.11, 0.06, 0.05 and 0.04 mg/kg, respectively) in various food categories were higher than those of the rest of REE. The mean ΣREE in all food samples of the 11 categories ranged between 0.04 and 1.41 mg/kg. In turn, the daily mean dietary exposure of the ΣREE was 1.62 μg/kg body weight (bw) in the general Chinese population, with a range of 1.61-2.80 μg/kg bw for the different sex/age groups. Among the 16 analyzed REE, the highest exposure levels corresponded to Ce, La and Y. The highest mean dietary exposure to these 3 REE were 0.54, 0.31 and 0.17 μg/kg bw, respectively. The sum of the exposures of these 3 REE accounted about 63% of the total exposure to the 16 analyzed REE. On the other hand, the most important contributors to the dietary intake of REE were vegetables and grains, with percentages of 45.3% and 28.6%, respectively. Although the level of REE in tea was the highest among all of the food categories, taking into account that the consumption of this product was comparatively very low, tea resulted in a low contribution (3.6%). Recently, Zhao et al. (2023) reported the results of a research whose main objective was to investigate the REE (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Sc and Y) levels in a number of samples of the most representing foods randomly selected from local wholesale agricultural markets in the Bayan Obo mining area (Inner Mongolia, China). The potential health risks of dietary exposure to these 16 REE was also assessed. The following samples were analyzed for the content of REE: 140 grain samples, 309 meat and aquatic samples, 153 vegetable samples, 15 fruit samples, 39 dairy samples, and 21 egg samples. The order of REE concentrations in all food samples was La > e > d > > r > c > Gd > Eu > m > Tb > Er > m > y > b > o > Lu. Among all the food analyzed, meat and aquatic samples showed the highest REE levels, followed by grains, fruits, eggs, vegetables and dairy products. La and Ce were the most concentrated REE in the analyzed samples. Regarding human dietary exposure, cereals showed the highest contribution of REE, meaning a major source of exposure. The mean EDI of the total REE was 0.275 g/kg/day (range: 0.116-0.512 μg/kg/day). This mean value is below the recommended safe daily average intake of REE (70 g/kg/day) (Dai et al., 2022). Also in China, Zhuang et al. (2023) measured the concentrations of 16 REE (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Sc and Y) in various agricultural products collected near a large light rare earth mining area in Shandong Province. Their dietary intakes by local residents were subsequently estimated. The analyzed samples included wheat, maize, dry beans, vegetables, fruits and eggs. Considering all samples, the mean value of total REE was 286.96 μg/kg, being the content of LREE, 270.18 μg/kg. It accounted for more than 94% of total REE. Among the LREE, Ce, La, Nd and Pr were the dominant elements. The content of HREE was 16.77 μg/kg. Wheat, leafy vegetables, and allium vegetables had the highest content of REE, being the main sources of dietary exposure to REE. In contrast, the lowest contents of REE were found in melons vegetables, root vegetables, fruits, and eggs. The EDI of REE was 4.20 μg/kg bw/day. This was a low level that did not exceed the acceptable daily intake. There were scarce differences in the intake of REE for the different age/gender groups of population.

## 7. Conclusions

Due to their expanding usage in a number of high-tech applications, REE are currently being of considerable importance for the modern world economy. A direct consequence of the increased use of these elements also means that REE are being now an emerging pollutant. Since its extensive use in a number of applications it may cause an increasing risk of environmental contamination (Brewer et al., 2022; Gwenzi et al., 2018). Consequently, there is also a potential increased human exposure to REE, elements on whose toxicity the available information are rather scarce (Hirano and Suzuki, 1996; Pagano et al., 2015; Brouziotis et al., 2022). It is more than probable that the use of REE will continue its increase in the next years. Therefore, exhaustive investigations aimed at establishing the human exposure and potential adverse effects of these elements are clearly required. In this paper, the results of the available studies focused mainly on determining the levels of REE in foodstuffs have been reviewed. As above indicated, the diet is the main route of exposure to metals for non-occupationally exposed subjects. Thus, to know the current dietary intake of REE is an important first step. The results of most studies here reviewed do not suggest potential health risks for the consumers of the analyzed freshwater and marine species of higher consumption, or derived from the intake of a number of vegetables, fruits, mushrooms and other various foodstuffs (honey, tea, rice, etc.). However, it should be expected that the environmental concentrations of REE will increase with the increased use of these elements, which could lead to increased levels of contamination of fish, vegetables, fruits, etc. Consequently, a continued monitoring of the levels of REE in food is strongly suggested. This monitoring is being already conducted with well-known toxic elements as arsenic, lead, cadmium or mercury, for example. To assess periodically the potential health risks of the dietary exposure to REE is, logically, another important issue. For this, it is essential to know/update the toxic effects of the 17 REE, for which information is not currently particularly abundant.

## Declarations

### *Credit author statement*

- Neus González: Writing – original draft
- José Luis Domingo: Conceptualization; Writing – review & editing

### *Conflict and/or 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.

*Funding*

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

*Acknowledgments*

Neus González would like to thank the Ministry of Universities and the Recovery, Transformation and Resilience Plan for the Margarita Salas grant (2021URV-MS-06), which is funded by the European Union - NextGenerationEU.

## References

- Akagi T, Edanami K (2017) Sources of rare earth elements in shells and soft-tissues of bivalves from Tokyo Bay. Mar. Chem. 194:55-62.
- Amyot M, Clayden MG, MacMillan GA, Perron T, Arscott-Gauvin A (2017) Fate and trophic transfer of rare earth elements in temperate lake food webs. Environ. Sci. Technol. 51:6009-6017.
- Bakhshalizadeh S, Liyafoyi AR, Mora-Medina R, Ayala-Soldado N (2023) Bioaccumulation of rare earth elements and trace elements in different tissues of the golden grey mullet (Chelon auratus) in the southern Caspian Sea. *Environ Geochem Health* 45:6533-6542.
- Bocio A, Nadal M, Domingo JL (2005) Human exposure to metals through the diet in Tarragona, Spain: temporal trend. *Biol. Trace Elem. Res.* 104:193-201.
- Brewer A, Dror I, Berkowitz B (2022) Electronic waste as a source of rare earth element pollution: Leaching, transport in porous media, and the effects of nanoparticles. Chemosphere 287(Pt 2):132217.
- Briant N, Le Monier P, Bruzac S, Sireau T, Araújo DF, Grouhel A (2021) Rare earth elemente in bivalves' soft tissues of French metropolitan coasts: Spatial and temporal distribution. *Arch. Environ. Contam. Toxicol.* 81:600-611.
- Brouziotis AA, Giarra A, Libralato G, Pagano G, Guida M, Trifuoggi M (2022) Toxicity of rare earth elements: An overview on human health impact. *Frontiers in Environ. Sci.* 10:948041.
- Chelyadina NS, Kapranov SV, Popov MA, Smirnova LL, Bobko NI (2023) Rare earth elements in different body parts of the mussel Mytilus galloprovincialis (Crimea, Black Sea) and assessment of associated human health risks from its consumption. *Mar. Pollut. Bull.* 195:115462.
- Cheng J, Ding C, Li X, Zhang T, Wang X (2015) Rare earth element transfer from soil to navel orange pulp *(Citrus sinensis Osbeck* cv. Newhall) and the effects on internal fruit quality. *PLoS One* 10:e0120618.
- Dai Y, Sun S, Li Y, Yang J, Zhang C, Cao R, Zhang H, Chen J, Geng N (2022) Residual levels and health risk assessment of rare earth elements in Chinese resident diet: A market-based investigation. *Sci. Total Environ.* 828:154119.
- de Souza AFL, Petenuci ME, Camparim R, Visentainer JV, da Silva AJI (2020) Effect of seasonal variations on fatty acid composition and nutritional profiles of siluriformes fish species from the amazon basin. *Food Res. Int.* 132:109051.

- Domingo JL (2016) Nutrients and chemical pollutants in fish and shellfish. Balancing health benefits and risks of regular fish consumption. *Crit. Rev. Food Sci. Nutr.* 56:979-988.
- Domingo JL, Bocio A, Falcó G, Llobet JM (2007)Benefits and risks of fish consumption Part I. A quantitative analysis of the intake of omega-3 fatty acids and chemical contaminants. *Toxicology* 230:219-226.
- Doulgeridou A, Amlund H, Sloth JJ, Hansen M, National Food Institute - Technical University of Denmark. (2020) Review of potentially toxic rare earth elements, thallium and tellurium in plant-based foods. *EFSA J.* 18(Suppl 1):e181101.
- Falandysz J (2021) Nutritional and other trace elements and their associations in raw king bolete mushrooms,*Boletus edulis.* *Int. J. Environ. Res. Public Health* 19(1):417.
- Falandysz J, Sapkota A, Mędyk M, Feng X (2017a)Rare earth elements in parasol mushroom Macrolepiota procera. *Food Chem.* 221:24-28.
- Falandysz J, Sapkota A, Dryżałowska A, Mędyk M, Feng X (2017b)Analysis of some metallic elements and metalloids composition and relationships in parasol mushroom Macrolepiota procera. *Environ. Sci. Pollut. Res. Int.* 24:15528-15537.
- Falandysz J, Nnorom IC, Mędyk M (2022)Rare earth elements in *Boletus edulis* (king bolete) mushrooms from Lowland and Montane areas in Poland. *Int. J. Environ. Res. Public Health* 19(15):8948.
- Falandysz J, Fernandes AR, Zhang J (2024) Critical review of rare earth elements (REE) in cultivated macrofungi. *Food Control* 155:110085.
- Figueiredo C, Oliveira R, Lopes C, Brito P, Caetano M, Raimundo J (2022)Rare earth elements biomonitoring using the mussel Mytilus galloprovincialis in the Portuguese coast: Seasonal variations. *Mar Pollut. Bull.* 175:113335.
- González N, Marquès M, Nadal M, Domingo JL (2021) Temporal trend of the dietary exposure to metals/metalloids: A case study in Tarragona County, Spain. *Food Res. Int.* 147:110469.
- Gowda SG, Minami Y, Gowda D, Furuko D, Chiba H, Hui SP (2021)Lipidomic analysis of non-esterified furan fatty acids and fatty acid compositions in dietary shellfish and salmon by UHPLC/LTQ-Orbitrap-MS. *Food Res. Int.* 144:110325.
- Guéguen M, Amiard JC, Arnich N, Badot PM, Claisse D, Guérin T, Vernoux JP. (2011)Shellfish and residual chemical contaminants: hazards, monitoring, and health risk assessment along French coasts. *Rev. Environ. Contam. Toxicol.* 213:55-111.
- Gwenzi W, Mangori L, Danha C, Chaukura N, Dunjana N, Sanganyado E (2018) Sources, behaviour, and environmental and human health risks of high-technology rare earth elements as emerging contaminants. *Sci. Total Environ.* 636:299-313.
- Henríquez-Hernández LA, Acosta-Dacal AC, Boada LD, Zumbado M, Serra-Majem L, Luzardo OP (2023) Concentration of essential, toxic, and rare earth elements in ready-to-eat baby purees from the Spanish market. *Nutrients* 15(14):3251.
- Hirano S, Suzuki KT (1996) Exposure, metabolism, and toxicity of rare earths and related compounds.*Environ. Health Perspect.* 104(Suppl 1):85-95.
- Howe A, Fung LH, Lalor G, Rattray R, Vutchkov M (2005)Elemental composition of Jamaican foods 1: a survey of five

food crop categories. *Environ. Geochem. Health* 27:19-30.

- Imran M, Nguyen A, Sultanbawa Y (2023) Quantification of rare earth elements in Australian and imported rice samples from different origins using ICP-MS. *Sci. Total Environ.* 895:164865.
- Jiang DG, Yang J, Zhang S, Yang DJ (2012) A survey of 16 rare Earth elements in the major foods in China. *Biomed. Environ. Sci.* 25:267-271.
- Jiao Y, Yang L, Kong Z, Shao L, Wang G, Ren X, Liu Y (2021) Evaluation of trace metals and rare earth elements in mantis shrimp Oratosquilla oratoria collected from Shandong Province, China, and its potential risks to human health. *Mar. Pollut. Bull.* 162:111815.
- Kalantzi I, Black KD, Pergantis SA, Shimmield TM, Papageorgiou N, Sevastou K, Karakassis I (2013) Metals and other elements in tissues of wild fish from fish farms and comparison with farmed species in sites with oxic and anoxic sediments. *Food Chem.* 141:680-694.
- Kollander B, Rodushkin I, Sundström B (2023) Multi-element assessment of potentially toxic and essential elements in new and traditional food varieties in Sweden. *Foods* 12(9):1831.
- Koutrotsios G, Danezis GP, Georgiou CA, Zervakis GI (2018) Rare earth elements concentration in mushroom cultivation substrates affects the production process and fruit-bodies content of Pleurotus ostreatus and Cyclocybe cylindracea. *J. Sci. Food Agric.* 98:5418-5427.
- Kowalczyk E, Givelet L, Amlund H, Sloth JJ, Hansen M (2022) Risk assessment of rare earth elements, antimony, barium, boron, lithium, tellurium, thallium and vanadium in teas. *EFSA J.* 20(Suppl 1):e200410.
- Li X, Chen Z, Chen Z, Zhang Y (2013) A human health risk assessment of rare earth elements in soil and vegetables from a mining area in Fujian Province, Southeast China. *Chemosphere* 93:1240-1246.
- Ma L, Dang DH, Wang W, Evans RD, Wang WX (2019) Rare earth elements in the Pearl River Delta of China: Potential impacts of the REE industry on water, suspended particles and oysters. *Environ. Pollut.* 244:190-201.
- Mayfield DB, Fairbrother A (2015) Examination of rare earth element concentration patterns in freshwater fish tissues. *Chemosphere* 120, 68-74.
- Mędyk M, Falandysz J (2022) Occurrence, bio-concentration and distribution of rare earth elements in wild mushrooms. *Sci. Total Environ.* 851(Pt 1):158159.
- Mędyk M, Falandysz J, Nnorom IC (2023) Scandium, yttrium, and lanthanide occurrence in Cantharellus cibarius and C. minor mushrooms. *Environ. Sci. Pollut. Res. Int.* 30:41473-41484.
- MHPRC, Ministry of Health of the People's Republic of China. Maximum levels of contaminants in foods (GB 2762–2005), Beijing, 2005.
- Mleczek M, Niedzielski P, Kalač P, Siwulski M, Rzymski P, Gąsecka M (2016) Levels of platinum group elements and rare-earth elements in wild mushroom species growing in Poland. *Food Addit. Contam. Part A Chem. Anal. Control Exp. Risk Assess.* 33:86-94.
- Mozaffarian D, Rimm EB (2006) Fish intake, contaminants, and human health: evaluating the risks and the benefits. *JAMA* 296:1885-1899.
- Oladipo HJ, Tajudeen YA, Taiwo EO, Muili AO, Yusuf RO, Jimoh SA, Oladipo MK, Oladunjoye IO, Egbewande OM, Sodiq YI, et al. (2023) Global environmental health impacts of rare earth metals: Insights for research and policy

making in Africa. *Challenges* 14(2):20.

- Pagano G, Guida M, Tommasi F, Oral R (2015) Health effects and toxicity mechanisms of rare earth elements-Knowledge gaps and research prospects. *Ecotoxicol. Environ. Saf.* 115:40-48.
- Pagano G, Thomas PJ, Di Nunzio A, Trifuoggi M (2019) Human exposures to rare earth elements: Present knowledge and research prospects. *Environ. Res.* 171:493-500.
- Pereira WVDS, Ramos SJ, Melo LCA, Braz AMS, Dias YN, Almeida GV, Fernandes AR (2022) Levels and environmental risks of rare earth elements in a gold mining area in the Amazon. *Environ. Res.* 211:113090.
- Perelló G, Vicente E, Castell V, Llobet JM, Nadal M, Domingo JL (2015) Dietary intake of trace elements by the population of Catalonia (Spain): results from a total diet study. *Food Addit. Contam. Part A Chem. Anal. Control Expo. Risk Assess.* 32:748-755.
- Pinto FR, Duarte AM, Silva F, Barroso S, Mendes S, Pinto E, Almeida A, Sequeira V, Vieira AR, Gordo LS, Gil MM (2022) Annual variations in the mineral element content of five fish species from the Portuguese coast. *Food Res. Int.* 158:111482.
- Reindl AR, Falkowska L (2021) Trace elements in the muscle, ova and seminal fluid of key clupeid representatives from the Gdansk Bay (South Baltic Sea) and Iberian Peninsula (North-East Atlantic). *J. Trace Elem. Med. Bio.l* 68:126803.
- Rodríguez-Hernández Á, Díaz-Díaz R, Zumbado M, Bernal-Suárez MDM, Acosta-Dacal A, Macías-Montes A, Travieso-Aja MDM, Rial-Berriel C, Henríquez Hernández LA, Boada LD, Luzardo OP (2022) Impact of chemical elements released by the volcanic eruption of La Palma (Canary Islands, Spain) on banana agriculture and European consumers. *Chemosphere* 293:133508.
- Santos ACSS, Souza LA, Araujo TG, de Rezende CE, Hatje V (2023) Fate and trophic transfer of rare earth elements in a tropical estuarine food web. *Environ. Sci. Technol.* 57:2404-2414.
- Shi Z, Yong L, Liu Z, Wang Y, Sui H, Mao W, Zhang L, Li Y, Liu J, Wei S, Song Y (2022) Risk assessment of rare earth elements in fruits and vegetables from mining areas in China. *Environ. Sci. Pollut. Res. Int.* 29:48694-48703.
- Shtangeeva I (2022) Accumulation of scandium, cerium, europium, hafnium, and tantalum in oats and barley grown in soils that differ in their characteristics and level of contamination. *Environ. Sci. Pollut. Res. Int.* 29:40839-40853.
- Siwulski M, Budka A, Rzymski P, Mleczek P, Budzyńska S, Gąsecka M, Szostek M, Kalač P, Kuczyńska-Kippen N, Niedzielski P, Goliński P, Magdziak Z, Kaniuczak J, Mleczek M (2020) Multiannual monitoring (1974-2019) of rare earth elements in wild growing edible mushroom species in Polish forests. *Chemosphere* 257:127173.
- Squadrone S, Brizio P, Stella C, Prearo M, Pastorino P, Serracca L, Ercolini C, Abete MC (2016) Presence of trace metals in aquaculture marine ecosystems of the northwestern Mediterranean Sea (Italy). *Environ. Pollut.* 215:77-83.
- Squadrone S, Brizio P, Battuello M, Nurra N, Sartor RM, Benedetto A, Pessani D, Abete MC (2017) A first report of rare earth elements in northwestern Mediterranean seaweeds. *Mar. Pollut. Bull.* 122(1-2):236-242.
- Squadrone S, Brizio P, Stella C, Mantia M, Battuello M, Nurra N, Sartor RM, Orusa R, Robetto S, Brusa F, Mogliotti P, Garrone A, Abete MC (2019) Rare earth elements in marine and terrestrial matrices of Northwestern Italy: Implications for food safety and human health. *Sci. Total Environ.* 660:1383-1391.
- Squadrone S, Brizio P, Stella C, Mantia M, Pederiva S, Brusa F, Mogliotti P, Garrone A, Abete MC (2020a) Trace

elements and rare earth elements in honeys from the Balkans, Kazakhstan, Italy, South America, and Tanzania. *Environ. Sci. Pollut. Res. Int.* 27:12646-12657.

- Squadrone S, Brizio P, Stella C, Pederiva S, Brusa F, Mogliotti P, Garrone A, Abete MC (2020b) Trace and rare earth elements in monofloral and multifloral honeys from Northwestern Italy; A first attempt of characterization by a multi-elemental profile. *J. Trace Elem. Med. Biol.* 61:126556.
- Squadrone S, Biancani B, Da Rugna C, Favaro L, Pederiva S, Abete MC (2022) Trace and rare earth element bioaccumulation in the spotted dogfish (Scyliorhinus stellaris). *Environ. Sci. Pollut. Res. Int.* 29:70262-70268.
- Tahboub YR, Al-Ghzawi AAA, Al-Zayafdneh SS, AlGhotani MS (2022) Levels of trace elements and rare earth elements in honey from Jordan. *Environ. Sci. Pollut. Res. Int.* 29:11469-11480.
- USGS, US Geological Survey (2023a) Rare Earth Statistics and Information. https://www.usgs.gov/centers/national-minerals-information-center/rare-earths-statistics-and-information (accessed: December 1, 2023).
- USGS, US Geological Survey (2023b) The Rare-Earth Elements— Vital to Modern Technologies and Lifestyles. https://pubs.usgs.gov/fs/2014/3078/pdf/fs2014-3078.pdf (accessed: December 1, 2023).
- Versa Electronics (2023). The Most Important Metals in Electronics Manufacturing – Rare Earth Metals https://versae.com/tag/rare-earth-metals/ (accessed: December 1, 2023).
- Vukojević V, Đurđić S, Stefanović V, Trifković J, Čakmak D, Perović V, Mutić J (2019) Scandium, yttrium, and lanthanide contents in soil from Serbia and their accumulation in the mushroom Macrolepiota procera (Scop.) Singer. *Environ. Sci. Pollut. Res. Int.* 26:5422-5434.
- Wang H, Chen X, Ye J, Jia X, Zhang Q, He H (2020) Analysis of the absorption and accumulation characteristics of rare earth elements in Chinese tea. *J. Sci. Food Agric.* 100:3360-3369.
- Wang XN, Gu YG, Wang ZH (2022) Rare earth elements in different trophic level marine wild fish species. *Environ. Pollut.* 292(Pt A):118346.
- Yang L, Wang X, Nie H, Shao L, Wang G, Liu Y (2016) Residual levels of rare earth elements in freshwater and marine fish and their health risk assessment from Shandong, China. *Mar. Pollut. Bull.* 107:393-397.
- Yang D, Sui H, Mao W, Wang Y, Yang D, Zhang L, Liu Z, Yong L, Song Y (2022) Dietary Exposure Assessment of Rare Earth Elements in the Chinese Population. *Int. J. Environ. Res. Public Health* 19:15583.
- Yin X, Martineau C, Demers I, Basiliko N, Fenton NJ (2021) The potential environmental risks associated with the development of rare earth element production in Canada. *Environ. Reviews* 29:354-377.
- Zapp P, Schreiber A, Marx J, Kuckshinrichs W (2022) Environmental impacts of rare earth production *MRS Bull.* 47:267–275.
- Zhang H, Deng L, Yang J, Jiang J, Shen Z, Xie J (2009) Rare earth elements in marine organisms from Shenzhen coastal region. *Wei Sheng Yan Jiu* 38:543-545 (in Chinese).
- Zhao C, Yang J, Zhang X, Fang X, Zhang N, Su X, Pang H, Li W, Wang F, Pu Y, Xia Y (2023) A human health risk assessment of rare earth elements through daily diet consumption from Bayan Obo Mining Area, China. *Ecotoxicol. Environ, Saf.* 266:115600.
- Zhuang M, Zhao J, Li S, Liu D, Wang K, Xiao P, Yu L, Jiang Y, Song J, Zhou J, Wang L, Chu Z (2017a) Concentrations and health risk assessment of rare earth elements in vegetables from mining area in Shandong, China.

*Chemosphere* 168:578-582.

- Zhuang M, Wang L, Wu G, Wang K, Jiang X, Liu T, Xiao P, Yu L, Jiang Y, Song J, Zhang J, Zhou J, Zhao J, Chu Z (2017b) Health risk assessment of rare earth elements in cereals from mining area in Shandong, China. *Sci. Rep.* 7(1):9772.
- Zhuang M, Xie H, Jiang Y, Xiao P, Wang K, Chu Z, Zhao J, Zhang T (2023) Probabilistic assessment of dietary rare earth elements intake among people living near a rare earth ore. *Sci. Total Environ.* 856(Pt 2):159141.