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Sulfur content in foods consumed in an Italian population and impact of diet quality on sulfur intake

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A R T I C L E I N F O

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A B S T R A C T

Sulfur is an essential nutrient but data about its intake are scarce. We aimed to measure sulfur content in food samples and assess its habitual intake in relation to adherence to healthy dietary patterns in 719 Italian adults. Using a food frequency questionnaire, we estimated overall sulfur intake, and its relation with adherence to healthy dietary patterns. The highest sulfur content was found in preserved/canned fish (3.0 g/kg), seafood (2.8 g/kg), white meat (2.8 g/kg) and dairy products, particularly aged cheeses (2.1 g/kg) and lowest in fresh fruit (87 mg/kg), oils and fats (157 mg/kg), and beverages (141 mg/kg), with the exception of onion and garlic (1.3 g/kg). The mean sulfur intake in the study population was 1.1 g/day, slightly higher in men than women. The foods contributing most to sulfur intake were meat (29%) and cereals (19%), with also substantial contribution (>10%) from beverages and dairy products. Adherence to dietary patterns had little influence on sulfur intake, except for adherence to MIND diet positively and linearly associated with sulfur intake. Our study provides an updated overview of sulfur content in foods composing the Italian diet, as well as of sulfur intake in an Italian community of Northern Italy.

1. Introduction

Sulfur (S) is the 16th chemical element of the periodic table with symbol S. It's a yellow colored, tasteless non-metal, common in nature in crystalline (native) and non-crystalline form. It is present in sulfide and sulfate form in many minerals and it is the structural basis of sulfur-containing amino acids (SAAs) such as methionine and cysteine (Brosnan and Brosnan, 2006; Nimni et al., 2007).

Most of the literature regarding sulfur intake considers the sulfur-containing amino acids (SAAs). Sulfur is excreted as sulfate, the urinary excretion of sulfate generally reflecting input from either inorganic or amino acid sources (Parcell, 2002). This highlights how sulfur is one of the most important naturally occurring elements for humans especially as it may concern dietary intake, and assessment of dietary habits may become essential to detect sulfur intake and its relationship to health status in humans (Bahrampour et al., 2022; Grimble, 2006; Osterholt et al., 2022).

A deficiency in sulfur intake can result in important clinical manifestations that may relate both to an increased risk of the onset of viral diseases and to the manifestation of clinical pictures such as joint pain, due to a deficiency in glycosaminoglycan synthesis, as well as alterations of skin, nail and hair, since sulfur is an important component of keratin and sulfur daily intake is necessary to balance loss to tissue growth (Cashman and Sloan, 2010; Roederer et al., 1992; van der Kraan et al., 1990). In addition, subjects with higher adherence to plant-based diet, especially vegan, are at higher risk of sulfur deficiency and should consider to increase intake of foods rich in sulfur (Doleman et al., 2017; Nimni et al., 2007). Conversely, intake of high amount of sulfur has been suggested to be harmless, however, excessive sulfur intake, especially in its inorganic form, may cause gastrointestinal disorders, including stomach discomfort and diarrhea (Mitchell, 2021) as well as imbalance of protein metabolism and immune function especially for the

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sulfur-containing amino acids (van de Poll et al., 2006).

Therefore, the assessment of sulfur intake is a relevant public health issue and this study aims to assess sulfur content in foods consumed by a community in Northern Italy, to estimate its intake and evaluate the relation with adherence to common healthy dietary patterns.

2. Materials and Methods

2.1. Food collection and analysis

Sulfur content of food products characterizing the eating pattern of Northern Italian population from the provinces of Modena and Reggio Emilia has been established by sampling products bought from local markets, supermarkets, canteens, delis and grocery stores, as previously described (Filippini et al., 2020b; Malavolti et al., 2020). Briefly, we identified foods most frequently consumed in a typical Italian diet. The final list of food categories included 'Cereals and cereals products' ('Pasta, other grains', 'Rice', 'Bread', and 'Crackers, crispbread, salty snacks'), 'Meat and meat products' (namely 'Red meat' including mainly beef, veal, pork and veal, 'White meat' including chicken and turkey, 'Processed meat', and 'Offal'), 'Milk and dairy products' (divided into 'Milk and yogurt', 'Fresh cheese', and 'Aged cheese'), 'Eggs', 'Fish and seafood' (divided into 'Preserved and tinned fish' like tinned tuna, 'Non-piscivorous fish' like cod, hake or flounder, and 'Piscivorous fish' like tuna or sword fish, and 'Crustacean and shellfish' including shrimps, octopus, cuttlefish or clams), 'All vegetables' (namely 'Leafy vegetables', 'Tomatoes', 'Root vegetables', 'Cabbage', 'Onion and garlic', and 'Other vegetables'), 'Mushrooms', 'Legumes', 'Potatoes', 'Fresh fruits' (divided into 'Citrus fruits' and 'All other fruits'), 'Dry fruits, nuts and seeds' (divided into 'Dry fruits' and 'Nuts and seeds'), 'Sweets, chocolate, cakes, etc.' (namely 'Sugar, confectionery not chocolate', 'Chocolate, candy bars, etc.', 'Ice-cream', 'Cakes, pies and pastries', and 'Biscuits, dry cakes'), 'Oils and fats' (divided into 'Vegetable fats and oils (not olive)', 'Olive oil', and 'Butter and other animal fats') and 'Beverages' (divided into non-alcoholic beverages: 'Coffee and tea', 'Fruit juices', and 'Soft drinks'; alcoholic beverages: 'Wines', 'Aperitif wines and beers', and 'Spirits and liqueurs') (Filippini et al., 2019; Malagoli et al., 2019).

We purchased selected food and beverages in two provinces of Emilia-Romagna region, namely Modena and Reggio Emilia in the period October 2016-February 2017. Foods were collected raw or cooked according the usual modality of consumption as specified in the EPIC-FFQ. For some food items including vegetables, e.g. leafy vegetables or tomatoes, both raw and cooked samples were analyzed. During sample handling, we tried to avoid element cross-contamination using different plastic food containers as well as plastic and stainless cutlery. We also used a food blender equipped with a stainless-steel blade. After homogenization, we aliquoted 0.5 g portion (wet weight) into quartz containers previously washed with MilliQ water (MilliQPlus, Millipore, MA, USA) and HNO_3. Sample digestion was performed using 10 ml solution (5 ml HNO_3 + 5 ml H_2O) in a microwave system (Discover SP-D, CEM Corporation, NC, USA). Digested material was stored in plastic tubes and diluted to 50 ml with deionized water before analysis. Food samples have been analyzed by inductively-coupled-plasma mass-spectrometry (Agilent 7500ce, Agilent Technologies, CA, USA), the method of choice in elemental speciation, covering a broad field of covalently bound elements, coordinated metals, metalloids and organometallic metabolites and large number of proteins bearing heteroelements such as sulfur.

All analyses were performed in duplicate, implementing standard quality controls as previously described, including blank solutions (MilliQ water, Millipore, MA, USA), and using a control solution of tap-water additionally enriched with 22 ppb of the element under investigation (Filippini et al., 2018a; Filippini et al., 2018b). A total of 939 food study samples were analyzed. Limit of quantification was 0.8 mg/kg for sulfur, with corresponding limits of detection (LOD) of 0.2 mg/kg. Samples of spices (e.g., garlic, cinnamon or paprika powder) and other food dressing (e.g., apple vinegar) were excluded from the study due to undetectable levels of sulfur.

2.2. Study population

For this study, we established habitual dietary intake of a Northern Italian community from 2005 to 2006 (Malagoli et al., 2015). From the population database of the Emilia-Romagna Region residents (population about 4000,000 inhabitants), using random selection from individuals enrolled in the National Health Service directories (mandatory for all residents) of five of the nine provinces of the Emilia-Romagna region (Bologna, Ferrara, Modena, Parma and Reggio Emilia) we identified 2825 potential suitable subjects. Potential participant were mailed an envelope containing information sheets, study questionnaires for assessment demographics, lifestyles and dietary habits (see below), informed consent form, and a pre-paid return envelope. A total of 747 (response rate of 26.4%) subjects were recruited among all residents in the study provinces to participate. This study complies with the Declaration of Helsinki and all subjects signed a written informed consent and returned study material for collection of individual characteristics.

2.3. Assessment of dietary habits

To evaluate dietary habits, we administrated the food frequency questionnaires (FFQ) implemented within the 'European Prospective Investigation into Cancer and Nutrition' (EPIC) project. The EPIC-FFQ is a validated semi-quantitative FFQ and we used the version specifically developed for the Northern Italy population (Pasanisi et al., 2002). Frequency and amount of consumption of 188 food items were estimated over the previous year. The dietary questionnaire was self-administered and the accuracy of completion of the EPIC-FFQ forms by participants was ensured through pictures of foods and serving sizes. For quality data control, we excluded participants reporting incomplete FFQs or with extreme and implausible values of energy intake, i.e. $<$ 0.5th or $>$ 99.5th percentile, based on the ratio of total energy intake to calculated basal metabolic rate, which excluded 28 subjects (Vinceti et al., 2011). The final study sample was 719 adult participants, 319 men and 400 women. The sample population did not include people with food restrictions, on a weight control diet, or vegetarian/vegan diet during the survey. We eventually estimated daily dietary intake (mg/day) as previously reported by multiplying the quantity of sulfur in food sample (mg/kg food as consumed) with the corresponding food intake determined from the FFQ (in g/day) (Filippini et al., 2018a; Malavolti et al., 2021).

For daily dietary intake, we also performed stratified analysis by sex and by adherence to the Greek Mediterranean Index (Trichopoulou et al., 2003), the Italian Mediterranean Index (Malagoli et al., 2015), the Dietary Approach to Stop Hypertension (DASH) diet (Appel et al., 1997), and to the Mediterranean-DASH Diet Intervention for Neurodegenerative Delay (MIND) diet, which combines the DASH and the Mediterranean patterns (Filippini et al., 2020a; Morris et al., 2015a).

The Greek Mediterranean Index (GMI) score is based on intake of 9 items (Trichopoulou et al., 2003): vegetables, legumes, fruit and nuts, dairy products, cereals, meat and meat products, fish, alcohol, and the ratio of monounsaturated fatty acids (MUFAs) to saturated fatty acids (FAs). For most items, consumption above the study median received 1 point; all other intake received 0 points. For dairy products and meat and meat products, consumption below the median received 1 point. Medians were sex specific. For ethanol, men who consumed 10–50 g/d and women who consumed 5–25 g/d received 1 point; otherwise, the score was 0. The range of possible scores was 0–9.

The Italian Mediterranean Index (IMI) was developed by the Epidemiology and Prevention Unit of the Milan National Cancer Institute (Agnoli et al., 2011) by adapting the GMI to typical Italian eating behavior. The score is based on intake of 11 items: 6 typical

Mediterranean foods or food groups (pasta; typical Mediterranean vegetables such as raw tomatoes, leafy vegetables, onion and garlic, salad, and fruiting vegetables, fruits, legumes, olive oil, and fish), 4 non-Mediterranean foods (soft drinks, butter, red meat, and potatoes), and alcohol consumption. One point has given for consumption of each typical Mediterranean food in the upper tertile of the distribution, and for consumption of each non-Mediterranean food in the bottom tertile; all other dietary components receive 0 points. Alcohol receives 1 point for intake up to 12 g/day; abstainers and persons who consumed > 12 g/day do not receive any point. The range of possible scores was 0–11.

The DASH diet was originally developed for lowering blood pressure and risk of cardiovascular diseases (Sacks et al., 2001). DASH scores were calculated based on eight components: fruits, vegetables, nuts and legumes, low-fat dairy products, whole grains, sodium, sweetened beverages, red and processed meats. Overall, possible scores ranged from 8 to 40, with higher scores indicating higher adherence (Filippini et al., 2020a).

The MIND pattern has 15 components originally developed with the aim at reducing the risk of dementia, includes 10 brain healthy food groups (green leafy vegetables, other vegetables, nuts, berries, beans, whole grains, white meat (fish and poultry), olive oil instead of other oil, and wine intake limitation) as well as decrease of 5 unhealthy food groups, including red meats, butter and stick margarine, cheese, pastries and sweets, and fried/fast food. Additional general guidelines for the MIND diet are eating at least three servings of whole grains, a salad and one other vegetable, and a glass of wine each day. In addition, nuts are used as a snack on most days and beans every other day. Poultry and berries are recommended at least twice a week and fish at least once a week. It is essential to limit the intake of the MIND diet's "unhealthy food groups", especially butter (less than 1 tablespoon a day), cheese, and fried or fast food (less than a serving a week for any of the three). Scores ranges from 0 to 15, with higher values meaning higher adherence (Morris et al., 2015b).

2.4. Data analysis

We used median values as cut points for identification of poor and high adherence for Mediterranean diet (both GMI and IMI), DASH and MIND dietary patterns. We also used non-linear spline regression model with three knots at fixed cutpoints (10th, 50th and 90th percentiles) to evaluate the relation between adherence to dietary patterns and sulfur intake, adjusting for potential confounders, namely age, sex, body mass index, and total energy intake.

3. Results

Characteristics of the study participants are reported in Table 1. In this study we included 719 participants, 319 men (mean age 59 years) 400 women (mean age 52 years). Nearly half of the participants graduated high school diploma or more and the vast majority lived with partners (regardless of the marriage). Body mass index (BMI) mean value was 25.5 demonstrating a tendency of the study population to normal-overweight. The mean energy intake was 1907 kcal/day, higher in men (2143 kcal/day) than in women (1932 kcal/day). Mean consumption of some food categories was similar for both sexes, except for slightly lower consumption of cereals, meat and beverages due to lower wine consumption in the female population, while males consumed fewer dairy products, tea, coffee, vegetables and citrus fruits (Supplemental Table S1).

The content of sulfur in 939 food samples is reported in Table 2. Laboratory analysis of this wide range of foods shows high variation in sulfur concentration: the highest levels were found in preserved and canned fish (3027 mg/kg), white meat (2788 mg/kg), seafood (2701 mg/kg), milk and dairy products, especially aged cheese (2078 mg/kg), and eggs (1924 mg/kg). Conversely, the lowest values were found in foods such as fresh fruits (87 mg/kg), all vegetables (655 mg/kg) except onion and garlic (1264 mg/kg), potatoes (463 mg/kg), oils and fats (157 mg/kg) especially olive oil (8 mg/kg), and all beverages (141 mg/kg) with the partial exception of coffee and tea (773 mg/kg).

Table 1
Characteristics of study participants. Number (percentage-%) reported when not otherwise indicated mean and standard deviation (SD).

	All		Men		Women	
	N	(%)	*N*	(%)	*N*	(%)
All subjects	719	(100)	319	(44.4)	400	(55.6)
Age (years)						
Mean (SD)	55.3	(14.5)	59.0	(14.0)	52.3	(14.1)
< 65	499	(69.4)	190	(59.6)	309	(77.2)
≥ 65	220	(30.1)	129	(40.4)	91	(22.8)
Education (years)						
≤5	170	(23.6)	86	(27.0)	84	(21.0)
6–8	178	(24.8)	86	(27.0)	92	(23.0)
9–13	268	(37.3)	101	(31.7)	167	(41.7)
≥ 14	103	(14.3)	46	(14.4)	57	(14.3)
Marital status						
Married/unmarried partner	493	(68.6)	239	(74.9)	254	(63.5)
Unmarried/single	104	(14.5)	42	(13.2)	62	(15.5)
Divorced	48	(6.7)	18	(5.6)	40	(7.5)
Widowed	74	(10.3)	20	(6.3)	54	(13.5)
Body mass index (kg/m^2)						
Mean (SD)	25.5	(3.9)	26.4	(3.4)	24.7	(4.1)
≤ 19	45	(6.3)	3	(0.9)	42	(10.5)
20–24	306	(42.6)	116	(36.4)	190	(47.5)
25–29	287	(39.9)	162	(50.8)	125	(31.2)
≥ 30	81	(11.3)	38	(11.9)	43	(10.8)
Energy (kcal/day)						
Mean (SD)	2026	(718)	2143	(747)	1932	(681)
GMI						
Mean (SD)	4.4	(1.7)	4.5	(1.7)	4.4	(1.7)
< 5	352	(49.0)	152	(47.6)	200	(50.0)
≥ 5	367	(51.0)	167	(52.4)	200	(50.0)
IMI						
Mean (SD)	4.1	(1.9)	4.1	(1.9)	4.1	(1.9)
< 4	275	(38.2)	129	(40.4)	146	(36.5)
≥ 4	444	(61.8)	190	(59.6)	254	(63.5)
DASH						
Mean (SD)	23.5	(5.0)	22.6	(5.0)	24.2	(4.8)
< 24	345	(48.0)	171	(53.6)	174	(43.5)
≥ 24	374	(52.0)	148	(46.4)	226	(56.5)
MIND						
Mean (SD)	7.4	(1.4)	7.3	(1.5)	7.4	(1.4)
< 7.5	328	(45.6)	156	(48.9)	172	(43.0)
≥ 7.5	391	(54.4)	163	(51.1)	228	(57.0)

Abbreviations: IMI, Italian Mediterranean Index; GMI, Greek Mediterranean Index; DASH, Dietary Approach to Stop Hypertension; MIND, Mediterranean–DASH Diet Intervention for Neurodegenerative Delay.

The dietary intakes of sulfur in the study population are reported in Table 3. Overall mean intake was 1.1 g/day. Foods contributing most to sulfur intake were meat (28.6%), cereals (18.5%) and followed by beverages (13.2%) and milk/dairy products (11.8%), with eggs, legumes, dried fruits and potatoes providing the least sulfur intake. Men had overall sulfur intake only slightly higher than women (1144.1 mg/day vs. 1069.1 mg/day). As regards food contribution, men compared to women showed higher contribution from meat (30.5% vs. 26.9%) and cereals (19.8% vs. 17.5%), while women demonstrated higher contribution from beverages (11.8% vs. 14.4%) and milk/dairy products (11.1% vs. 12.4%).

As shown in Tables 4–7, there is no remarkable variation in sulfur concentration between the different results from the analyses regarding adherence to the GMI, IMI, DASH and MIND dietary patterns and the sulfur intake using median value as cut-point. As a matter of that, subjects with higher adherence to GMI, IMI and MIND diets showed approximately 10% higher total sulfur intake (Tables 4, 5 and 7), while we found the opposite for DASH diet, with higher intake for adherence below the median value (Table 6). Nonetheless, we can observe that

Table 2
Sulfur content (mg/kg) according to different food categories. Mean, standard deviation (SD) and range are reported.

Foods (N = 936)	N	Mean (SD)	Range
Cereals and cereal products	**100**	**1150 (286)**	**179–1980**
Pasta, other grains	39	1237 (352)	179–1980
Rice	7	969 (222)	675–1404
Bread	35	1100 (186)	737–1416
Crackers, crispbread, salty snacks	19	1128 (268)	546–1521
Meat and meat products	**94**	**2456 (812)**	**910–5158**
Red meat	35	2292 (657)	1075–3883
White meat	13	2788 (1040)	1583–4833
Processed meat	36	2497 (898)	910–5158
Offal	10	2455 (578)	1892–3439
Milk and dairy products	**88**	**1587 (793)**	**58–3107**
Milk and yogurt	13	293 (83)	58–388
Cheese	75	1812 (627)	128–3107
Fresh cheese	26	1311 (568)	129–2634
Aged cheese	49	2078 (480)	1105–3107
Eggs	**7**	**1924 (350)**	**1294–2417**
Fish and seafood	**70**	**2582 (685)**	**610–3745**
Fish	54	2547 (681)	610–3718
Preserved and tinned fish	15	3027 (555)	2101–3718
Non-piscivorous fish	19	2212 (463)	610–2802
Piscivorous fish	20	2504 (755)	1241–3694
Crustaceans and mollusks	16	2701 (704)	1223–3745
All vegetables	**183**	**655 (763)**	**1–5057**
Leafy vegetables	33	589 (618)	112–2492
Tomatoes	21	271 (318)	78–1326
Root vegetables	14	240 (166)	1–582
Cabbage	27	1085 (613)	130–2706
Onion and garlic	31	1264 (1245)	231–5057
Other vegetables	57	400 (406)	55–2074
Mushrooms	**4**	**776 (34)**	**748–819**
Legumes	**38**	**1215 (763)**	**144–3130**
Potatoes	**11**	**463 (249)**	**247–993**
Fresh fruits	**60**	**87 (45)**	**2–218**
Citrus fruits	14	100 (25)	54–134
All other fruits	46	83 (49)	2–218
Dry fruits, nuts and seeds	**49**	**1549 (888)**	**37–3802**
Dry fruits	10	742 (731)	37–2475
Nuts and seeds	39	1756 (810)	428–3802
Sweets, chocolate, cakes, etc.	**84**	**815 (453)**	**5–2663**
Sugar, confectionery not chocolate	8	525 (717)	5–2096
Chocolate, candy bars, etc.	25	989 (347)	497–2216
Ice-cream	6	135 (118)	51–359
Cakes, pies and pastries	28	802 (454)	269–2663
Biscuits, dry cakes	17	957 (146)	763–1254
Oils and fats	**27**	**157 (486)**	**2–2244**
Vegetable fats and oils (not olive)	13	111 (363)	2–1318
Olive oil	4	8 (4)	5–13
Butter and other animal fats	10	275 (692)	4–2244
Beverages	**124**	**141 (295)**	**1–2309**
Coffee and tea	9	773 (878)	2–2309
Wines	66	117(75)	19–364
Red wine	35	138 (86)	31–364
White wine	31	93 (54)	19–235
Aperitif wines and beers	11	99 (62)	12–232
Spirits and liqueurs	21	21 (54)	1–247
Fruit juices	12	79 (71)	9–212
Soft drinks	5	69 (63)	24–179

there are little differences in daily sulfur intake when considering individual food categories: adherence above the median to the GMI diet involves a slightly increase of sulfur intake from cereal consumption (224.2 mg/day vs. 183.6 mg/day); likewise dietary sulfur intake from fish and seafood (105.6 mg/day vs. 69.5 mg/day), vegetables (91.9 mg/day vs. 55.1 mg/day) and legumes (30.8 mg/day, vs. 14.3 mg/day) is heightened. Similarly, adherence to IMI diet showed higher contribution from fish and seafood (97.1 mg/day vs. 73.1 mg/day), all vegetables (87.2 mg/day vs. 52.3 mg/day), legumes (26.6 mg/day vs. 16.5 mg/day) and fresh fruits (27.7 mg/day vs. 18.7 mg/day) but lower from meat products (298.9 mg/day vs. 340.7 mg/day). As mentioned above, higher adherence to DASH diet demonstrated higher contribution from milk and dairy products (139.8 mg/day vs. 119.9 mg/day), all

Table 3
Sulfur intake (mg/day) according to different food categories for the whole study population and by sex. Mean and standard deviation (SD) are reported.

	All (N = 719)	Men (N = 319)	Women (N = 400)
	Mean (SD)	Mean (SD)	Mean (SD)
Total	**1102.4 (369.8)**	**1144.1 (357.7)**	**1069.1 (376.4)**
Cereals and cereal products	**204.3 (110.3)**	**226.0 (117.0)**	**187.0 (101.5)**
Pasta, other grains	70.6 (50.3)	86.7 (56.1)	57.8 (41.1)
Rice	5.4 (7.4)	6.0 (8.4)	4.8 (6.4)
Bread	86.2 (79.2)	92.3 (80.8)	81.3 (77.6)
Crackers, crispbread, salty snacks	42.1 (32.5)	40.9 (35.2)	43.1 (30.2)
Meat and meat products	**314.9 (173.0)**	**348.9 (177.7)**	**287.8 (164.4)**
Red meat	154.3 (103.0)	175.6 (113.1)	137.3 (90.7)
White meat	82.4 (73.1)	87.4 (72.0)	78.5 (73.8)
Processed meat	73.6 (62.2)	80.6 (67.8)	68.1 (56.7)
Offal	4.5 (11.3)	5.3 (12.8)	3.9 (9.9)
Milk and dairy products	**129.8 (93.0)**	**126.5 (87.5)**	**132.5 (97.2)**
Milk and yogurt	56.9 (65.1)	47.5 (57.0)	64.3 (70.0)
Cheese	73.0 (60.7)	79.0 (66.4)	68.2 (55.3)
Fresh cheese	19.2 (24.9)	15.6 (20.3)	22.0 (27.7)
Aged cheese	53.8 (49.9)	63.4 (57.3)	46.2 (41.7)
Eggs	**29.0 (21.9)**	**28.0 (21.6)**	**29.7 (22.1)**
Fish and seafood	**88.0 (69.1)**	**89.5 (65.4)**	**86.7 (72.0)**
Fish	68.4 (55.9)	70.6 (53.9)	66.6 (57.4)
Preserved and tinned fish	28.1 (32.4)	31.0 (29.4)	25.8 (34.4)
Non-piscivorous fish	23.1 (27.4)	23.9 (29.2)	22.5 (25.8)
Piscivorous fish	17.2 (25.5)	15.8 (22.7)	18.3 (27.5)
Crustaceans and mollusks	19.6 (27.6)	18.9 (25.8)	20.1 (29.0)
All vegetables	**73.9 (47.7)**	**74.2 (47.4)**	**73.6 (48.0)**
Leafy vegetables	18.3 (15.1)	17.0 (13.6)	19.2 (16.2)
Tomatoes	15.2 (12.0)	17.5 (13.6)	13.3 (10.3)
Root vegetables	3.4 (4.7)	2.6 (4.0)	4.0 (5.1)
Cabbage	4.5 (7.7)	4.2 (8.7)	4.8 (6.7)
Onion and garlic	22.2 (27.7)	23.9 (27.8)	20.8 (27.6)
Other vegetables	10.4 (7.7)	9.0 (6.5)	11.4 (8.4)
Mushrooms	**2.0 (3.1)**	**1.9 (3.2)**	**2.0 (2.9)**
Legumes	**22.8 (22.6)**	**23.7 (23.5)**	**22.0 (21.9)**
Potatoes	**11.4 (11.2)**	**11.8 (12.2)**	**11.0 (10.3)**
Fresh fruits	**24.3 (14.4)**	**23.5 (14.1)**	**24.9 (14.5)**
Citrus fruits	18.0 (11.3)	17.2 (11.1)	18.6 (11.4)
All other fruits	6.3 (5.0)	6.3 (4.9)	6.3 (5.0)
Dry fruits, nuts and seeds	**2.6 (4.7)**	**2.7 (4.4)**	**2.4 (5.0)**
Dry fruits	0.3 (0.8)	0.3 (0.9)	0.3 (0.7)
Nuts and seeds	2.3 (4.5)	2.4 (4.0)	2.2 (4.8)
Sweets, chocolate, cakes, etc.	**52.0 (53.7)**	**49.9 (56.6)**	**53.7 (51.4)**
Sugar, confectionery not chocolate	3.6 (4.3)	3.4 (3.5)	3.8 (4.9)
Chocolate, candy bars, etc.	5.2 (8.6)	4.8 (8.4)	5.5 (8.8)
Ice-cream	1.9 (2.1)	1.8 (2.3)	1.9 (1.9)
Cakes, pies and pastries	28.1 (43.5)	27.2 (49.3)	28.9 (38.2)
Biscuits, dry cakes	13.2 (16.4)	12.6 (16.5)	13.6 (16.3)
Oils and fats	**2.2 (2.3)**	**2.5 (2.4)**	**2.0 (2.3)**
Vegetable fats and oils (not olive)	0.3 (0.7)	0.3 (0.7)	0.2 (0.6)
Olive oil	0.2 (0.1)	0.2 (0.1)	0.2 (0.1)
Butter and other animal fats	1.8 (2.2)	2.0 (2.3)	1.6 (2.1)
Beverages	**145.4 (111.7)**	**134.9 (85.4)**	**153.8 (128.4)**
Coffee and tea	117.5 (108.8)	98.0 (79.8)	133.1 (125.2)
Wines	15.1 (19.8)	23.1 (23.0)	8.7 (13.8)
Red wine	10.3 (16.4)	16.1 (19.9)	5.7 (11.1)
White wine	4.8 (9.5)	7.0 (11.5)	3.1 (7.0)
Aperitif wines and beers	3.9 (10.9)	4.7 (9.8)	3.2 (11.7)
Spirits and liqueurs	0.1 (0.2)	0.1 (0.3)	0.1 (0.1)
Fruit juices	5.8 (11.8)	6.0 (11.4)	5.6 (12.1)
Soft drinks	3.1 (8.2)	3.1 (7.0)	3.0 (9.0)

Table 4
Distribution of sulfur daily dietary intake below (<5) and above (≥5) the median adherence to the Greek Mediterranean Index (GMI) diet (in mg/day). Mean and standard deviation (SD) are reported.

	GMI< 5 (N = 352)	GMI≥ 5 (N = 367)
	Mean (SD)	Mean (SD)
Total	**1031.8 (321.4)**	**1170.0 (399.9)**
Cereals and cereal products	**183.6 (102.1)**	**224.2 (114.3)**
Pasta, other grains	65.1 (44.1)	75.9 (55.2)
Rice	4.6 (6.6)	6.1 (8.0)
Bread	73.9 (76.9)	98.0 (79.6)
Crackers, crispbread, salty snacks	40.0 (31.1)	44.2 (33.8)
Meat and meat products	**316.3 (152.9)**	**313.5 (190.6)**
Red meat	159.9 (93.3)	148.9 (111.3)
White meat	73.3 (70.8)	91.2 (74.3)
Processed meat	79.2 (62.5)	68.3 (61.5)
Offal	3.9 (10.9)	5.1 (11.7)
Milk and dairy products	**131.5 (96.9)**	**128.2 (89.3)**
Milk and yogurt	53.1 (68.2)	60.4 (61.8)
Cheese	78.4 (60.7)	67.8 (60.2)
Fresh cheese	21.9 (28.3)	16.6 (20.9)
Aged cheese	56.5 (48.8)	51.2 (50.9)
Eggs	**26.5 (19.4)**	**31.3 (23.7)**
Fish and seafood	**69.5 (60.8)**	**105.6 (72.0)**
Fish	54.3 (52.0)	81.9 (56.2)
Preserved and tinned fish	23.6 (33.7)	32.4 (30.4)
Non-piscivorous fish	18.2 (23.5)	27.8 (29.9)
Piscivorous fish	12.5 (20.8)	21.7 (28.6)
Crustaceans and mollusks	15.2 (20.9)	23.7 (32.3)
All vegetables	**55.1 (32.1)**	**91.9 (53.0)**
Leafy vegetables	14.2 (13.7)	22.1 (15.4)
Tomatoes	12.5 (10.5)	17.8 (12.9)
Root vegetables	2.2 (3.4)	4.6 (5.5)
Cabbage	3.3 (6.0)	5.7 (8.9)
Onion and garlic	14.9 (17.8)	29.1 (33.2)
Other vegetables	7.9 (6.5)	12.7 (8.1)
Mushrooms	**1.4 (1.9)**	**2.5 (3.8)**
Legumes	**14.3 (16.8)**	**30.8 (24.5)**
Potatoes	**10.6 (11.0)**	**12.1 (11.3)**
Fresh fruits	**20.0 (13.1)**	**28.4 (14.4)**
Citrus fruits	14.9 (10.6)	21.0 (11.2)
All other fruits	**5.1 (4.5)**	**7.4 (5.2)**
Dry fruits, nuts and seeds	1.9 (3.5)	3.2 (5.6)
Dry fruits	0.2 (0.7)	0.3 (0.9)
Nuts and seeds	1.7 (3.2)	2.8 (5.3)
Sweets, chocolate, cakes, etc.	**57.4 (57.7)**	**46.8 (49.1)**
Sugar, confectionery not chocolate	3.4 (3.7)	3.8 (4.8)
Chocolate, candy bars, etc.	5.8 (9.5)	4.6 (7.7)
Ice-cream	1.8 (2.1)	1.9 (2.1)
Cakes, pies and pastries	32.2 (47.4)	24.3 (39.0)
Biscuits, dry cakes	14.2 (17.9)	12.2 (14.7)
Oils and fats	**2.3 (2.3)**	**2.2 (2.3)**
Vegetable fats and oils (not olive)	0.2 (0.6)	0.3 (0.7)
Olive oil	0.1 (0.1)	0.2 (0.1)
Butter and other animal fats	1.9 (2.2)	1.7 (2.2)
Beverages	**141.3 (104.7)**	**149.4 (118.1)**
Coffee and tea	115.1 (101.2)	119.9 (115.7)
Wines	13.9 (20.9)	16.2 (18.6)
Red wine	8.8 (17.2)	11.7 (15.5)
White wine	5.1 (10.5)	4.5 (8.5)
Aperitif wines and beers	3.9 (13.1)	3.8 (8.2)
Spirits and liqueurs	0.1 (0.3)	0.1 (0.2)
Fruit juices	4.7 (9.7)	6.8 (13.4)
Soft drinks	3.1 (7.2)	3.1 (8.6)

Table 5
Distribution of sulfur daily dietary intake below (<4) and above (≥4) the median adherence to the Italian Mediterranean Index (IMI) diet (in mg/day). Mean and standard deviation (SD) are reported.

	IMI< 4 (N = 275)	IMI≥ 4 (N = 444)
	Mean (SD)	Mean (SD)
Total	**1076.9 (338.8)**	**1118.2 (387.3)**
Cereals and cereal products	**200.8 (111.1)**	**206.4 (109.9)**
Pasta, other grains	64.1 (47.1)	74.7 (51.9)
Rice	4.7 (6.2)	5.8 (8.0)
Bread	90.4 (84.5)	83.6 (75.7)
Crackers, crispbread, salty snacks	41.7 (29.7)	42.4 (34.1)
Meat and meat products	**340.7 (160.4)**	**298.9 (178.7)**
Red meat	174.8 (101.2)	141.6 (102.1)
White meat	75.7 (66.2)	86.6 (76.8)
Processed meat	86.4 (68.0)	65.7 (56.9)
Offal	3.8 (10.0)	4.9 (12.0)
Milk and dairy products	**122.5 (88.2)**	**134.4 (95.7)**
Milk and yogurt	49.2 (63.3)	61.6 (65.8)
Cheese	73.3 (57.9)	72.8 (62.4)
Fresh cheese	19.5 (22.1)	19.0 (26.5)
Aged cheese	53.8 (47.1)	53.8 (51.6)
Eggs	**28.1 (19.6)**	**29.5 (23.2)**
Fish and seafood	**73.1 (58.2)**	**97.1 (73.6)**
Fish	55.9 (47.9)	76.2 (59.0)
Preserved and tinned fish	25.7 (35.4)	29.6 (30.3)
Non-piscivorous fish	17.4 (19.1)	26.7 (30.9)
Piscivorous fish	12.8 (18.7)	19.9 (28.5)
Crustaceans and mollusks	17.3 (21.6)	21.0 (30.7)
All vegetables	**52.3 (27.8)**	**87.2 (52.3)**
Leafy vegetables	12.3 (9.9)	22.0 (16.6)
Tomatoes	11.4 (8.0)	17.5 (13.5)
Root vegetables	2.0 (2.5)	4.3 (5.5)
Cabbage	2.9 (4.7)	5.5 (8.9)
Onion and garlic	16.3 (18.7)	25.8 (31.5)
Other vegetables	7.6 (5.2)	12.1 (8.5)
Mushrooms	**1.7 (2.2)**	**2.1 (3.5)**
Legumes	**16.5 (15.8)**	**26.6 (25.2)**
Potatoes	**11.5 (7.9)**	**11.3 (12.9)**
Fresh fruits	**18.7 (10.8)**	**27.7 (15.2)**
Citrus fruits	13.7 (8.2)	20.7 (12.1)
All other fruits	5.1 (4.3)	7.1 (5.2)
Dry fruits, nuts and seeds	**2.5 (5.2)**	**2.6 (4.4)**
Dry fruits	0.3 (0.7)	0.3 (0.9)
Nuts and seeds	2.3 (5.0)	2.3 (4.1)
Sweets, chocolate, cakes, etc.	**56.0 (57.3)**	**49.5 (51.3)**
Sugar, confectionery not chocolate	3.9 (4.2)	3.5 (4.4)
Chocolate, candy bars, etc.	5.6 (9.1)	4.9 (8.3)
Ice-cream	2.0 (2.0)	1.8 (2.2)
Cakes, pies and pastries	32.0 (47.8)	25.7 (40.4)
Biscuits, dry cakes	12.6 (16.2)	13.5 (16.5)
Oils and fats	**2.5 (2.6)**	**2.0 (2.1)**
Vegetable fats and oils (not olive)	0.2 (0.4)	0.3 (0.8)
Olive oil	0.1 (0.1)	0.2 (0.1)
Butter and other animal fats	2.1 (2.5)	1.6 (1.9)
Beverages	**149.8 (103.2)**	**142.7 (116.7)**
Coffee and tea	117.5 (102.5)	117.6 (112.6)
Wines	18.1 (20.4)	13.2 (19.1)
Red wine	11.6 (16.9)	9.5 (16.1)
White wine	6.4 (11.2)	3.8 (8.1)
Aperitif wines and beers	4.3 (9.2)	3.6 (11.8)
Spirits and liqueurs	0.1 (0.3)	0.1 (0.2)
Fruit juices	5.4 (9.6)	6.0 (13.0)
Soft drinks	4.5 (8.7)	2.2 (7.7)

vegetables (87.0 mg/day vs. 59.7 mg/day), legumes (29.8 mg/day vs. 15.1 mg/day) and fresh fruits (29.0 mg/day vs. 19.2 mg/day), while lower from cereals (189.7 mg/day vs. 220.1 mg/day), meat products 267.1 mg/day vs. 366.7 mg/day). Finally, higher adherence to MIND diet demonstrated higher contribution from fish and seafood (105.6 mg/day vs. 67.0 mg/day), all vegetables (87.2 mg/day vs. 58.0 mg/day) and beverages (151.6 mg/day vs. 138.1 mg/day).

Spline analysis of the relation between increasing adherence to the investigated dietary patterns and sulfur intake confirmed the substantial lack of association except for a positive trend with MIND diet (Fig. 1).

4. Discussion

This study has been conceived to provide an estimation of dietary intake of sulfur in the Northern Italy population providing in particular insights on the relation with adherence to different dietary habits. Data from sulfur intake are scarce in the literature and to the best of our knowledge they are especially missing for the Italian population (SINU, 2014). Previous data reported lower daily dietary intake around 850–930 mg/day (Emsley, 1998) compared to our results. In addition, a previous study evaluating sulfur intake in a small UK population found

Table 6
Distribution of sulfur daily dietary intake below (<24) and above (≥24) the median adherence to the Dietary Approaches to Stop Hypertension (DASH) diet (in mg/day). Mean and standard deviation (SD) are reported.

	DASH< 24 (N = 345)	DASH≥ 24 (N = 374)
	Mean (SD)	Mean (SD)
Total	**1125.5 (391.7)**	**1081 (347.6)**
Cereals and cereal products	**220.1 (116.5)**	**189.7 (102.3)**
Pasta, other grains	80.5 (57.5)	61.5 (40.6)
Rice	4.9 (6.4)	5.9 (8.2)
Bread	93.9 (85.0)	79.0 (72.8)
Crackers, crispbread, salty snacks	40.8 (30.5)	43.3 (34.2)
Meat and meat products	**366.7 (180.5)**	**267.1 (151.0)**
Red meat	185.2 (109.2)	125.8 (87.8)
White meat	78.3 (75.5)	86.3 (70.7)
Processed meat	98.5 (69.5)	50.7 (43.5)
Offal	4.7 (12.3)	4.3 (10.2)
Milk and dairy products	**119.0 (91.5)**	**139.8 (93.4)**
Milk and yogurt	41.6 (56.4)	71.0 (69.2)
Cheese	77.4 (66.4)	68.9 (54.6)
Fresh cheese	19.4 (22.6)	18.9 (26.9)
Aged cheese	58.0 (56.6)	49.9 (42.5)
Eggs	**28.2 (22.4)**	**29.7 (21.4)**
Fish and seafood	**81.4 (69.9)**	**94.0 (67.9)**
Fish	61.4 (57.1)	74.9 (54.0)
Preserved and tinned fish	26.7 (38.0)	29.4 (26.1)
Non-piscivorous fish	19.6 (22.9)	26.3 (30.6)
Piscivorous fish	15.0 (25.1)	19.1 (25.7)
Crustaceans and mollusks	20.0 (27.9)	19.1 (27.4)
All vegetables	**59.7 (36.3)**	**87.0 (52.9)**
Leafy vegetables	14.9 (14.3)	21.4 (15.2)
Tomatoes	14.1 (12.4)	16.2 (11.6)
Root vegetables	2.1 (3.3)	4.7 (5.4)
Cabbage	3.3 (5.7)	5.7 (9.0)
Onion and garlic	17.3 (19.1)	26.7 (33.2)
Other vegetables	8.1 (6.5)	12.5 (8.2)
Mushrooms	**1.9 (2.3)**	**2.0 (3.7)**
Legumes	**15.1 (14.9)**	**29.8 (26.0)**
Potatoes	**12.1 (12.4)**	**10.7 (9.9)**
Fresh fruits	**19.2 (12.0)**	**29.0 (14.8)**
Citrus fruits	14.0 (9.0)	21.7 (11.9)
All other fruits	5.2 (4.7)	7.3 (5.1)
Dry fruits, nuts and seeds	**2.0 (3.7)**	**3.1 (5.5)**
Dry fruits	0.2 (0.7)	0.3 (0.9)
Nuts and seeds	1.7 (3.4)	2.7 (5.3)
Sweets, chocolate, cakes, etc.	**57.2 (56.9)**	**47.1 (50.2)**
Sugar, confectionery not chocolate	3.6 (4.0)	3.6 (4.6)
Chocolate, candy bars, etc.	5.5 (9.0)	4.9 (8.3)
Ice-cream	2.0 (2.2)	1.7 (2.0)
Cakes, pies and pastries	33.8 (47.8)	22.9 (38.4)
Biscuits, dry cakes	12.3 (15.7)	14.0 (17.0)
Oils and fats	**2.7 (2.6)**	**1.8 (1.9)**
Vegetable fats and oils (not olive)	0.3 (0.6)	0.3 (0.7)
Olive oil	0.1 (0.1)	0.2 (0.1)
Butter and other animal fats	2.3 (2.5)	1.3 (1.7)
Beverages	**140.2 (86.6)**	**150.2 (130.6)**
Coffee and tea	108.1 (82.2)	126.2 (128.0)
Wines	17.8 (22.3)	12.6 (16.7)
Red wine	11.4 (18.5)	9.3 (14.2)
White wine	6.4 (11.8)	3.3 (6.4)
Aperitif wines and beers	4.3 (9.8)	3.4 (11.8)
Spirits and liqueurs	0.1 (0.3)	0.1 (0.1)
Fruit juices	5.1 (10.0)	6.5 (13.2)
Soft drinks	4.8 (9.5)	1.5 (6.4)

little lower mean intakes of 930–950 mg/day depending on the estimation method (Doleman et al., 2017). Similarly to our study, the main sources from cereals, meat and dairy products, with also contribution of some foods rich in sulfur like garlic and cruciferous vegetables demonstrated high content also in our sample.

In view of results obtained in our study, the sulfur intake does not differ according to the most important healthy dietary pattern GMI, IMI and DASH suggesting that also low adherence is sufficient to meet daily requirements. Conversely, adherence to MIND diet showed a substantial positive association.

Our findings also indicate that low sulfur intake is unlikely in our population, thus avoiding risk of sulfur deficiency. Sulfur is an important nutrient for both humans and animals and proteins contain between 3% and 6% of sulfur amino acids, namely methionine and cysteine

Table 7
Distribution of sulfur daily dietary intake below (<7.5) and above (≥7.5) the median adherence to the Mediterranean–DASH Diet Intervention for Neurodegenerative Delay (MIND) diet (in mg/day). Mean and standard deviation (SD) are reported.

	MIND< 7.5 (N = 328)	MIND≥ 7.5 (N = 391)
	Mean (SD)	Mean (SD)
Total	**1043.3 (320.4)**	**1151.9 (400.4)**
Cereals and cereal products	**204.9 (104.2)**	**203.8 (115.3)**
Pasta, other grains	75.8 (53.5)	66.3 (47.1)
Rice	5.2 (7.0)	5.5 (7.8)
Bread	83.9 (74.1)	88.1 (83.2)
Crackers, crispbread, salty snacks	40.1 (29.9)	43.8 (34.5)
Meat and meat products	**312.4 (151.3)**	**317.0 (189.5)**
Red meat	164.3 (99.7)	146.0 (105.0)
White meat	63.9 (61.3)	98.0 (78.4)
Processed meat	80.5 (59.3)	67.8 (64.0)
Offal	3.6 (10.6)	5.2 (11.8)
Milk and dairy products	**122.8 (84.7)**	**135.8 (99.2)**
Milk and yogurt	48.6 (57.7)	63.8 (69.9)
Cheese	74.2 (58.8)	72.0 (62.3)
Fresh cheese	19.8 (24.0)	18.6 (25.6)
Aged cheese	54.3 (47.7)	53.4 (51.7)
Eggs	**26.8 (20.0)**	**30.8 (23.1)**
Fish and seafood	**67.0 (53.1)**	**105.6 (75.8)**
Fish	52.0 (44.1)	82.1 (60.9)
Preserved and tinned fish	21.7 (21.4)	33.5 (38.5)
Non-piscivorous fish	18.3 (24.8)	27.2 (28.8)
Piscivorous fish	12.0 (18.5)	21.5 (29.5)
Crustaceans and mollusks	14.9 (20.2)	23.4 (32.1)
All vegetables	**58.0 (37.8)**	**87.2 (50.9)**
Leafy vegetables	14.0 (13.7)	21.8 (15.3)
Tomatoes	14.5 (12.2)	15.8 (11.9)
Root vegetables	2.4 (3.7)	4.3 (5.3)
Cabbage	2.7 (4.4)	6.0 (9.4)
Onion and garlic	16.8 (19.0)	26.7 (32.7)
Other vegetables	7.7 (6.7)	12.6 (7.9)
Mushrooms	**1.4 (1.9)**	**2.4 (3.7)**
Legumes	**16.7 (20.8)**	**27.9 (22.9)**
Potatoes	**10.7 (10.6)**	**11.9 (11.7)**
Fresh fruits	**20.2 (12.6)**	**27.7 (14.9)**
Citrus fruits	14.7 (9.3)	20.8 (12.0)
All other fruits	5.6 (5.1)	6.9 (4.8)
Dry fruits, nuts and seeds	**1.7 (3.5)**	**3.2 (5.4)**
Dry fruits	0.2 (0.6)	0.4 (0.9)
Nuts and seeds	1.5 (3.3)	2.9 (5.2)
Sweets, chocolate, cakes, etc.	**60.3 (58.4)**	**45.0 (48.4)**
Sugar, confectionery not chocolate	3.6 (3.4)	3.7 (4.9)
Chocolate, candy bars, etc.	5.5 (9.3)	4.9 (8.0)
Ice-cream	1.9 (2.1)	1.8 (2.1)
Cakes, pies and pastries	33.4 (50.0)	23.7 (36.6)
Biscuits, dry cakes	16.0 (17.2)	10.8 (15.3)
Oils and fats	**2.3 (2.0)**	**2.2 (2.5)**
Vegetable fats and oils (not olive)	0.3 (0.6)	0.2 (0.7)
Olive oil	0.1 (0.1)	0.2 (0.1)
Butter and other animal fats	1.8 (1.9)	1.7 (2.4)
Beverages	**138.1 (90.6)**	**151.6 (126.6)**
Coffee and tea	110.3 (85.3)	123.6 (124.9)
Wines	14.8 (20.7)	15.3 (19.0)
Red wine	9.5 (17.1)	11.0 (15.9)
White wine	5.3 (10.6)	4.3 (8.5)
Aperitif wines and beers	4.5 (13.5)	3.3 (8.1)
Spirits and liqueurs	0.1 (0.3)	0.1 (0.2)
Fruit juices	5.2 (9.4)	6.3 (13.5)
Soft drinks	3.1 (7.2)	3.0 (8.9)

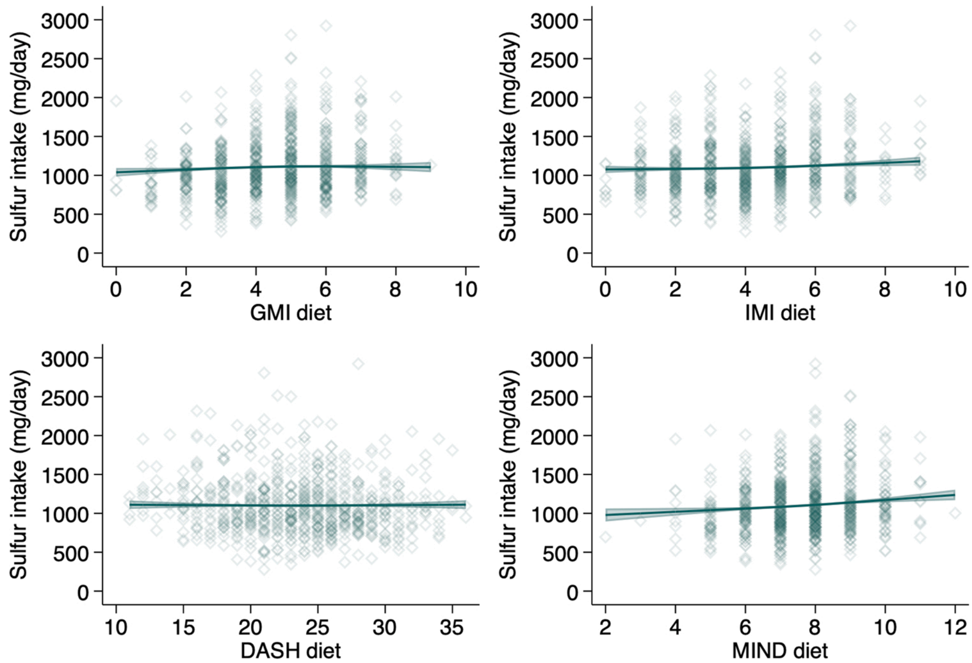

Fig. 1. Spline regression analysis of the relation between adherence to dietary patterns (the Greek Mediterranean Index-GMI diet, the Italian Mediterranean Index-IMI diet, the Dietary Approach to Stop Hypertension-DASH diet, and the Mediterranean-DASH Diet Intervention for Neurodegenerative Delay.-MIND diet) and daily intake of sulfur (mg/day). Diamonds indicate individual values, solid lines the overall estimates while shaded area the 95% confidence interval.

(Komarnisky et al., 2003; Nimni et al., 2007; Townsend et al., 2004). Generally, a balanced diet provides adequate intake (Mitchell, 2021), however, certain conditions, such as low-protein diets, unbalanced vegan diets or malabsorption status may cause sulfur deficiency, with consequent defects in cartilage synthesis and increase risk of arthritis (van der Kraan et al., 1990). In addition, human immunodeficiency virus (HIV) positive individuals have been shown to have reduced levels of acid-soluble thiols, particularly cysteine and glutathione (GSH), in plasma and leukocytes (Roederer et al., 1992). Interestingly, the impairment of immunological functions in HIV positive patients results at least partly from cysteine deficiency. As a matter of that, immune reconstitution using N-acetyl-cysteine administration may be recommended for HIV patients with and without anti-retroviral therapy (Breitkreutz et al., 2000).

Conversely at high concentrations, sulfur may causes damage in both animals and humans (Mitchell, 2021). An excessive level of sulfur-containing compounds in domestic ruminant rations has been associated with polio encephalomalacia and secondary metabolic disorders (Olkowski, 1997). Despite the literature in humans is scarce: ingestion of high amount of sulfur has been associated with relapse in ulcerative colitis patients (Jowett et al., 2004). In addition, high intake of sulfur amino acids has been associated with increased risk of diabetes and cardiometabolic diseases (Dong et al., 2022a; Dong et al., 2020; Dong et al., 2022b). High sulfur diet may play an important role in colorectal cancer and early-onset colorectal cancer with a mechanisms related to gut microbiome and specifically byproducts of sulfite-reducing bacteria which generate hydrogen sulfide, a harmful compound that may induce DNA damage, disrupt the mucus bilayer, and promote inflammation and colorectal cancer (Wang et al., 2021), highlighting the relevance to monitor sulfur intake, especially from processed meat and canned fish (Moon et al., 2023).

A major question that arises in connection with dietary supplements that provide organic forms of sulfur, is whether the diet could account for differences in response amongst individuals. It is possible that the individuals that benefit mostly from these supplements are those that consume inadequate amounts of proteins or other sources of dietary sulfate (Nimni et al., 2007). In this perspective, particular interest should be paid on restrictive diets towards those foods that involve higher percentages of sulfur, in particular diets with low protein content, calorie restriction or vegetarian and vegan (Ingenbleek and Kimura, 2013), notably if not properly balanced or associated with other risk factors like in subjects with higher than average requirements, such as athletes or people with HIV (Parcell, 2002).

The main strength of our study is the measurement of sulfur content in a large number of food samples and beverages representing habitual diet of Northern Italy population. Therefore, we were able to assess daily sulfur intakes with a high accuracy.

Some limitations of the study must be acknowledged. The analysis hampered the assessment of sulfur speciation and contribution of inorganic and organic sulfur compounds, although these latter should be the most reported in food samples and contributing to dietary intake (Bergamasco et al., 2022). Secondly, we did not evaluate health status of the study subjects including gastrointestinal diseases affecting sulfur absorption, nor we recruited a population sample representative of the general population in terms of age distribution or occupation. In addition, our results cannot be generalized to other vulnerable populations e.g., children and the elderly. Since the recruitment period was carried out during 2005–2006 period, dietary habits of the population may have changed over time. Moreover, food collection was carried out mainly during winter and autumn, thus we could only partially account for possible seasonal variation in sulfur content in food (Filippini et al., 2019). However, considering the lack of data on sulfur intake, still our results may provide an estimation of sulfur intake in Northern Italy using a large number of food samples and beverages representing their habitual diet. Conversely, the EPIC-FFQ is a validated tool that includes tailored questions to assess intake of foods generally limited to a specific season (Pisani et al., 1997). For this reason, no substantial variation due to month of collection is expected.

5. Conclusions

Our study provides an update of the contribution of a wide range of foods to sulfur intake in a Northern Italy community, and of the contribution to sulfur intake of different dietary patterns. Higher adherence to 'healthy' dietary patterns appears to have little effect on sulfur intake, except for a positive association with the MIND diet. Thereby, future studies should include populations with different eating habits and adherence to diets other than the ones here investigated, in order to further assess dietary intake of sulfur in a Western population like the Italian one.

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CRediT authorship contribution statement

TF and MV conceived the study. LV performed laboratory analysis. MM and CB evaluated dietary habits. AP, AR and TF prepared the database and performed statistical analysis. All authors interpreted the data. AP and AR drafted the first manuscript with contribution of TF. All authors read and approved the final manuscript.

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.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jfca.2023.105543.

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