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# Sustainability analysis of the Mediterranean diet: results from the French NutriNet-Santé study#

Julia Baudry[1]*†, Floriane Neves[1]†, Denis Lairon[2], Benjamin Allès[1], Brigitte Langevin[3], Joséphine Brunin[1], Florine Berthy[1], Ina Danquah[4], Mathilde Touvier[1], Serge Hercberg[1,5], Marie-Josèphe Amiot[6], Philippe Pointereau[3] and Emmanuelle Kesse-Guyot[1]

[1]*Université Sorbonne Paris Nord and Université Paris Cité, Inserm, INRAE, CNAM, Centre of Research in Epidemiology and StatisticS (CRESS), Nutritional Epidemiology Research Team (EREN), F-93017 Bobigny, France*

[2]*Aix Marseille Université, Inserm, INRAE, C2VN, Marseille, France*

[3]*Solagro, Voie TOEC Toulouse, France*

[4]*Heidelberg Institute of Global Health (HIGH), Medical Faculty and University Hospital, Heidelberg University, Heidelberg, Germany*

[5]*Département de Santé Publique, Hôpital Avicenne, Bobigny, France*

[6]*MoISA, Univ Montpellier, CIHEAM-IAMM, CIRAD, INRAE, Institut Agro, IRD, Montpellier, France*

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## Abstract

The Mediterranean diet is often proposed as a sustainable diet model. This study aimed to evaluate the associations between adherence to the Mediterranean diet and sustainability domains in a cohort of French adults, using multiple criteria including nutritional quality, environmental pressures, monetary cost and dietary pesticide exposure. Food intakes of 29 210 NutriNet-Santé volunteers were assessed in 2014 using a semi-quantitative FFQ. Adherence to the Mediterranean diet was evaluated using the validated literature-based adherence score (MEDI-LITE). The associations between the MEDI-LITE and various sustainability indicators were examined using ANCOVA models, adjusted for sex, age and energy intake. Higher adherence to the MEDI-LITE was associated with higher nutritional quality scores, better overall nutrient profile as well as reduced environmental impact (land occupation: Q5 *v.* Q1: −35 %, greenhouse gas emissions: −40 % and cumulative energy demand: −17 %). In turn, monetary cost increased with increasing adherence to the Mediterranean diet (Q5 *v.* Q1: +15 %), while higher adherents to the Mediterranean diet had overall higher pesticide exposure due to their high plant-based food consumption. In this large cohort of French adults, greater adherence to the Mediterranean diet was associated with nutritional and environmental benefits, but also with higher monetary cost and greater exposure to pesticides, illustrating the necessity to develop large-scale strategies for healthy, safe (pesticide- and contaminant-free) and environmentally sustainable diets for all.

**Key words: Mediterranean diet: Nutritional quality: Environmental impact: Monetary cost: Pesticide exposure**

Our current food system is not sustainable and will not enable us to achieve the objectives defined by different international organisations, including the Paris agreement targets[1,2]. First, Western diets, characterised by energy-dense foods, high intakes of red and processed meat, processed food, salt and sugar and reduced intakes of complex carbohydrates, fibre, fruits and vegetables, are major risk factors for morbidity and mortality worldwide[2]. Second, current food systems account for 20 to 30 % of total greenhouse gas emissions (GHGE)[3] and 50 % of land use[4]. Dominant practices of food production also contribute to biodiversity loss and degradation of natural resources[5]. Third, emerging studies conducted in the general population suggest potential adverse health effects of pesticide residues contained in food[6–8]. Finally, many people do not have access to, or cannot afford, a healthy and sustainable diet[1,9]. These trends will likely worsen in a context of a growing world population, while many planetary boundaries have been already crossed, threatening planetary habitability[10].

**Abbreviations:** CED, cumulative energy demand; GHGE, greenhouse gas emissions; LO, land occupation; MDS, Mediterranean diet score; MEDI-LITE, literature-based adherence score to the Mediterranean diet; MET, Metabolic Equivalent of Task.

* **Corresponding author:** Julia Baudry, email julia.baudry@inrae.fr

† These authors contributed equally to this work

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In 2010, sustainable diets have been defined by the UN FAO as diets that bring nutritious and safe food for all, are economically equitable and affordable, do not jeopardise natural resources, and ensure food security for current and future generations[11].

The Mediterranean dietary pattern, which is characterised by a high consumption of fruits, vegetables, wholegrain cereals, legumes, nuts, olive and olive oil, a moderate consumption of fish and poultry, and a low consumption of meat[12], is often promoted as a healthy and environmentally sustainable diet that is socioculturally acceptable and has positive local economic benefits[13]. The traditional Mediterranean 'lifestyle' expands the concept to other components, such as adequate rest, physical activity, frugality, dietary diversity or personal involvement (i.e. conviviality including culinary preparation with others and shared meals)[14]. It is also recommended to favour local, seasonal, ecological and minimally processed foods that promote biodiversity[15].

The health benefits of the Mediterranean diet have been extensively studied, and studies showing inverse associations between adherence to a Mediterranean diet and non-communicable diseases, such as type 2 diabetes or metabolic syndrome, but also certain types of cancers, are numerous[16]. In addition, a large trial demonstrated that a Mediterranean diet supplemented with extra-virgin olive oil or tree nuts reduces the incidence of major cardiovascular events compared with individuals following a reduced-fat diet among high cardiovascular risk individuals[17].

While a large body of evidence has highlighted the health benefits of adherence to Mediterranean dietary patterns[18], fewer studies have examined the environmental impact of these diets. In general, they tended to suggest that Mediterranean diets may have lower environmental impacts than Western diets[19,20]. Furthermore, according to a recent meta-analysis, the Mediterranean diet does not appear more expensive than other diets[20], although some studies have yielded divergent results[21,22].

In addition, few studies have evaluated other diet sustainability features[21], in particular safety aspects (such as pesticide exposure), using quantitative data[23]. It is, however, of great importance to evaluate the sustainability of the Mediterranean diet in all its complexity to gain a more complete understanding of its potential as a sustainable diet[24,25].

In that context, the primary goal of this study was to examine the relationship between adherence to the Mediterranean diet and various sustainability features (nutritional quality, environmental pressures, monetary cost and dietary pesticide exposure), in line with the FAO definition of sustainable diets, in a large cohort of French adults. We also investigated whether higher adherence to the Mediterranean diet was related to some other Mediterranean lifestyle principles.

## Methods and data

### Study population

The NutriNet-Santé study is a prospective observational cohort of French adult volunteers launched in May 2009 and based on the Internet[26]. Upon inclusion in the cohort, participants completed a set of self-administered questionnaires about dietary intake, health, socio-economic status, physical activity, anthropometric and lifestyle characteristics. As part of the follow-up, volunteers are regularly invited to update their socio-demographic, lifestyle, dietary and health data and also to fill in optional questionnaires regarding dietary behaviours.

This study was conducted according to guidelines laid down in the Declaration of Helsinki. All procedures were approved by the Institutional Review Board of the Institut National de la Santé et de la Recherche Médicale (IRB INSERM no. 0000388FWA00005831) and the Commission Nationale de l'Informatique et des Libertés (CNIL no. 908 450 and no. 909 216). It is registered at ClinicalTrials.gov with the number NCT03335644. Electronic informed consent was signed by all participants at inclusion.

### Dietary intake assessment

Food intake was assessed using a semi-quantitative FFQ (called Org-FFQ) administered from June to December 2014. The Org-FFQ was built upon a pre-existing validated FFQ[27] to which statements regarding organic food consumption were added. In brief, participants had to detail their consumption of 264 items over the preceding year in order to estimate their total food intake. More specifically, they had to complete the frequency and the portion size or quantity of each food item[28]. In addition to providing the latter, participants were also asked to report the consumption frequency in their organic form of each food item, by ticking one of the following frequency modalities: never, rarely, half-of-time, often or always. To obtain organic food consumption, a weight of 0, 0·25, 0·5, 0·75 and 1 was applied to the respective frequencies. More detailed information about the Org-FFQ and sensitivity analyses regarding the weighting were published elsewhere[29]. Nutrient values were derived from a published food composition database[30].

### Mediterranean diet scores

Two scores were used in order to evaluate the adherence to the Mediterranean diet (online Supplementary Table 1): the validated literature-based adherence score to the Mediterranean diet (MEDI-LITE)[31,32], as the primary exposure, and the historical Mediterranean diet score (MDS)[12]. The MEDI-LITE is composed of six beneficial components that are typical of the Mediterranean diet (fruits, vegetables, cereals, legumes, fish and olive oil), two moderation components for which consumption is to be limited (meat and dairy products) and an alcohol component. Each food group is divided into three categories using fixed cut-offs (online Supplementary Table 1). The cut-offs have been proposed by Sofi et al., based on a comprehensive meta-analysis[32]. For the beneficial food groups, 2 points are given to the highest category of consumption, 1 to the middle category and 0 to the lowest category. A reverse scoring is applied for the moderation components, that is, 2 points for the lowest category, 1 for the middle category and 0 for the highest category. For the alcohol component, the scoring was as follows: 2 points if the intake was comprised between 12 and 24 g, 1 point if < 12 g and 0 points if > 24 g. The final score ranges from 0 to 18 points[32].

In a sensitivity analysis, we also considered the Mediterranean Diet Scale (MDS) by Trichopoulou et al.[12] which is based on the same components as the MEDI-LITE, but the attribution of points for each component depends on the sex-specific median. For beneficial components, 1 point is assigned when the consumption is at or above the median and 0 point when the consumption is below the median. For moderation components, 1 point is assigned when the consumption is below the median, 0 otherwise. Regarding alcohol, 1 point is attributed if the intake is comprised in the range of 10–50 g for men and 5–25 g for women, 0 points otherwise[12].

### Nutritional quality assessment

Three *a priori* scores were used to assess overall nutritional quality of the diet. First, we employed the food-based simplified *Programme National Nutrition Santé* Guidelines Score 2 (sPNNS-GS2), ranging from $-\infty$ to 14·25, which measures adherence to the French official nutrition guidelines based on epidemiological evidence[33]. Second, we constructed the nutrient-based Probability of Adequate Nutrient intake Diet score (PANDiet), ranging from 0 to 100, which reflects adequacy of the diet to the current French nutrient reference values[34]. Third, we computed the comprehensive diet quality index (cDQI), which allows to differentiate the consumption of healthful and unhealthful plant-based and animal food groups[35]. It ranges from 0 to 85 and includes seventeen components (eleven plant-based food and six animal-based foods). Healthful plant- and animal-based foods are scored positively and reversely for unhealthful plant- and animal-based foods. More information regarding the computation of the cDQI is available elsewhere[35].

### Environmental impact assessment

A detailed description of the development of the environmental indicators has been given elsewhere[36]. Briefly, the environmental indicators were assessed per d using the life cycle assessment methodology and the system boundaries were cradle-to-farm. The following indicators were used: GHGE in $kgCO_2e/kg$, the cumulative energy demand (CED) in MJ/kg and land occupation (LO) in $m^2/kg$. A database associated with the Org-FFQ items was created with the indicators, considering the food production system (conventional or organic). For this purpose, a comprehensive tool named DIALECTE, developed by the non-profit organisation Solagro, was used[37]. It assesses the agro-environmental performance of French farming systems, based on approximately 2000 farms, including organic farms. The environmental footprint of sixty agricultural items was estimated with this tool, completed by a literature review for thirty-two products. The GHGE, CED and LO of each food item in both their organic and conventional version were determined. The three diet-related GHGE, CED and LO were then obtained by multiplying the food quantity consumed (g/d) by each respective environmental indicator value, considering the production system.

### Monetary cost assessment

Participants were asked to complete a questionnaire in 2014 concerning attitudes and motivations regarding food choices and food places of supply. The KANTAR® database 2012 was used to obtain the prices for each of the 264 food items according to the place of supply and considering the method of food production (organic *v.* conventional)[38]. Moreover, 1962 additional prices were collected by the Bioconsom'acteurs association between 2014 and 2015 to assess the price of each food item in short supply chains. We obtained the individual monetary cost by multiplying the price (€/g) by the quantities consumed (g/d) considering the place of supply and the food production system.

### Pesticide exposure assessment

Data regarding pesticide residues came from the Chemisches und Veterinäruntersuchungsamt Stuttgart (CVUAS) database. The CVUAS[39] is an official regional state food control and health laboratory located in Germany, which analyses pesticides and contaminants in plant-source products, available on the German market, but the products come from eighty-eight countries. This database does not contain any animal products; however, data are available for both organically and conventionally grown products. Since all products are from the German market, they are subject to the European Union standards (as France) regarding organic agriculture[40]. In the present work, analytical results for 4 years (2012–2015) were used, leading to a database comprising more than 6·7 million data points (including 1 million for organic plant foods). Amongst molecules available in the CVUAS database, for which a sufficient number of plant foods was covered (for instance, the dithiocarbamates were not retained due to lack of data despite their frequent quantification in plant products), we selected some twenty pesticides, given their frequency of quantification exceeding the maximum residue levels and their frequency above toxicological reference values, using data from the 2015 EFSA report[41], as described elsewhere[42]. Three active substances authorised in organic farming were additionally included. The estimated daily intake (EDI) (expressed in μg/kg of weight per d) under the lower-bound scenario for each pesticide and each participant was calculated using the following formula[43]:

$$EDI = \sum_{k=1}^{n\_i} E_{i,j} = \left(C_{i,k} \times L_{k,j}\right) \div Bw_i$$

where $E_{i,j}$ is the estimated daily exposure to pesticide $j$ for the individual $i$ (μg/kg bw/d), $n_i$ is the number of plant foods in the diet of individual $i$, $C_{i,k}$ is the mean daily intake of plant food $k$ by individual $i$ (g/d), $L_{k,j}$ is the concentration of pesticide $j$ in food $k$ (mg/kg) and $Bw_i$ is the body weight of individual $i$ (kg).

### Assessment of practices associated with the Mediterranean lifestyle

Certain specific practices are related to the Mediterranean lifestyle, beyond diet composition; therefore, we also investigated, through


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different sociocultural different proxy markers of the Mediterranean lifestyle, whether adherence to the Mediterranean diet was associated with physical activity, consumption frequency of ready-to-use products and consumption of organic food. Physical activity levels, as marker of recommended physical activity, were determined using the International Physical Activity Questionnaire[44,45]. Three levels of physical activity were established based on the Metabolic Equivalent of Task (MET) minutes per week (MET-min/week): low (< 600 MET-min/week), moderate (600–1500 MET-min/week) and high (> 1500 MET-min/week).

The consumption frequency of ready-to-use products was also examined as a marker of proxy of culinary activities or sociality around food. In the aforementioned questionnaire used to retrieve food supply places, a question pertaining to the consumption frequency of canned, chilled and frozen foods was also asked. These consumptions were declared by each participant through five categories: never, rarely, half of the time, often and always and a weighting of 0, 0·25, 0·5, 0·75 and 1 point was assigned to each category. The final score is the sum of points multiplied by the weighting[46].

The organic food proportion in the diet was evaluated, as a marker of eco-friendly product consumption, as the ratio of total food consumed in organic (g/d) to total food consumed (g/d) without water.

### Statistical analyses

NutriNet-Santé participants who filled out the Org-FFQ between June and December 2014 were included in the present study (*n* 37 685). Of these, we excluded participants with missing covariates (*n* 380), who were detected as under- or over-reporters and who were living overseas (*n* 2852), and with missing data regarding the place of supply for the computation of diet monetary cost (*n* 5243), leaving a sample of 29 210 participants (online Supplementary Fig. 1). Participants were ranked and divided into sex-specific quintiles (Qi), according to the MEDI-LITE distribution. Baseline participants characteristics across levels of adherence to the Mediterranean diet were presented as mean and standard deviation. *P*-values refer to tests for linear contrast across quintiles for continuous variables, and Mantel-Haenszel $\chi^2$ trend tests or $\chi^2$ test, for ordinal and categorial variables, respectively.

Normality was assessed using graphical methods (histograms and Q-Q plots). To identify the associations between each sustainability indicator and adherence to the Mediterranean diet, ANCOVA models, with Tukey's adjustment, according to the observed margins, were used, providing adjusted means and 95 % CI. Two different models were computed: a model which was unadjusted (model 1) and a model adjusted for age, sex and total daily energy intake (main model, model 2). The latter model enabled us to study diet composition, beyond energy intake. *P*-values across quintiles were estimated using linear contrast tests.

The relationships between the various indicators and adherence to Mediterranean diet were also examined using the MEDI-LITE as a continuous variable, and results were expressed as $\beta$ per 1 SD and 95 % CI.

Sensitivity analyses were also performed to assess the robustness of our results by computing the MDS. Thus, the same analyses were performed to evaluate the associations between each sustainability indicator and adherence to the Mediterranean diet, using the MDS.

To allow comparability, the two Mediterranean scores were standardised in models with the main exposure modelled as a continuous variable. Two-sided tests were used, and a *P*-value < 0·05 was set for statistical significance. SAS (version 9.4; SAS Institute, Inc.) was used to perform data management and statistical analyses.

## Results

### Sample characteristics

The MEDI-LITE in the study sample ranged from 1 to 18[32]. Table 1 shows the characteristics of the study sample across quintiles of adherence to the MEDI-LITE. By construction, participants in Q1 were the least adherent (6·05 (SD = 1·13)) to the Mediterranean diet, and those in Q5 were the most adherent (13·94 (SD = 1·06)). Participants with the highest adherence to the Mediterranean diet (Q4 and Q5) were the oldest. Postgraduate participants represented 63·62 % of Q1 and 67·16 % of Q5. The lowest proportion of employees and manual workers was found in Q5, and the highest proportions of participants with high-level incomes were found in the highest quintiles.

Participants in Q5 were more often never-smokers and less often current smokers than other quintiles. Regarding the BMI, participants in Q1 had a mean of 24·63 kg/m$^2$ (SD = 5) and those in Q5 had a mean of 23·45 kg/m$^2$ (SD = 4·07).

### Adherence to the Mediterranean diet and diet sustainability

Online Supplementary Table 2 shows the intake for the different MEDI-LITE components. Adherence to the Mediterranean diet, modelled as quintiles, and the different diet sustainability features are presented in Fig. 1 (multivariable models). A positive association was observed between adherence to the MEDI-LITE score and the sPNNS-GS2 (Q5 *v.* Q1: +470 %), the PANDiet (Q5 *v.* Q1: +15 %), and the cDQI (Q5 *v.* Q1: +22 %). LO (Q5 *v.* Q1: –35 %), GHGE (Q5 *v.* Q1: –40 %) and CED (Q5 *v.* Q1: –17 %) decreased across quintiles. Diet monetary cost gradually increased across quintiles, the differences between Q5 compared with Q1 were 1·05€/d for the total diet monetary cost (Q5 *v.* Q1: +15 %), –1·72€/d for the cost dedicated to conventional foods (Q5 *v.* Q1: –29 %) and 2·76€/d for the cost dedicated to organic foods (Q5 *v.* Q1: +204 %).

Unadjusted models pertaining to the associations between the various sustainability indicators and the MEDI-LITE are shown in online Supplementary Table 3. Overall, the same trends were observed, apart from CED, for which the unadjusted models yielded opposite results.

Regarding nutrients (adjusted models), total energy intake gradually increased across MEDI-LITE quintiles while intake of ethanol decreased (Table 2). Higher adherents to the MEDI-LITE



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**Table 1.** General characteristics according to sex-specific quintiles of adherence to the Mediterranean diet (MEDI-LITE), *n* 29 210, 2014, NutriNet-Santé study*

| | Quintiles of level of adherence to the Mediterranean diet | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Q1 | | | Q2 | | | Q3 | | | Q4 | | | Q5 | | | |
| | % | Mean | SD | % | Mean | SD | % | Mean | SD | % | Mean | SD | % | Mean | SD | *P*† |
| MEDI-LITE | | 6·05 | 1·13 | | 8·54 | 0·50 | | 10·00 | 0·00 | | 11·45 | 0·50 | | 13·94 | 1·06 | < 0·0001 |
| Age (years) | | 49·69 | 14·88 | | 53·20 | 14·13 | | 54·27 | 13·73 | | 55·24 | 13·23 | | 55·18 | 13·21 | < 0·0001 |
| Women (%) | 75·14 | | | 75·21 | | | 75·15 | | | 74·29 | | | 73·97 | | | 0·39 |
| Education level (%) | | | | | | | | | | | | | | | | 0·0001 |
| Less than high school diploma | 20·95 | | | 22·36 | | | 22·83 | | | 21·02 | | | 19·40 | | | |
| High school diploma | 15·43 | | | 14·92 | | | 14·59 | | | 14·73 | | | 13·44 | | | |
| Postgraduate | 63·62 | | | 62·72 | | | 62·58 | | | 64·25 | | | 67·16 | | | |
| Occupation status (%) | | | | | | | | | | | | | | | | < 0·0001 |
| Unemployed | 4·30 | | | 3·65 | | | 3·86 | | | 3·98 | | | 4·66 | | | |
| Never employed | 7·24 | | | 6·63 | | | 5·97 | | | 6·43 | | | 8·14 | | | |
| Self-employed and Farmer | 1·77 | | | 1·74 | | | 1·45 | | | 1·78 | | | 1·93 | | | |
| Employee and manual worker | 18·60 | | | 15·33 | | | 13·57 | | | 12·95 | | | 10·91 | | | |
| Intermediate professionals | 16·52 | | | 14·91 | | | 14·71 | | | 13·94 | | | 13·53 | | | |
| Managerial staff | 22·59 | | | 20·76 | | | 21·00 | | | 20·70 | | | 20·18 | | | |
| Retired | 28·98 | | | 36·98 | | | 39·44 | | | 40·23 | | | 40·66 | | | |
| Monthly income per unit household unit (%) | | | | | | | | | | | | | | | | < 0·0001 |
| Unwilling to answer | 5·87 | | | 5·83 | | | 6·21 | | | 6·04 | | | 6·40 | | | |
| < €1200 | 13·34 | | | 11·45 | | | 10·50 | | | 10·72 | | | 11·87 | | | |
| €1200–1800 | 26·01 | | | 22·98 | | | 22·61 | | | 21·98 | | | 22·22 | | | |
| €1800–2700 | 27·24 | | | 28·26 | | | 28·30 | | | 27·22 | | | 26·44 | | | |
| > €2700 | 27·54 | | | 31·48 | | | 32·37 | | | 34·04 | | | 33·07 | | | |
| Region (%) | | | | | | | | | | | | | | | | < 0·0001 |
| Parisian basin | 17·57 | | | 14·98 | | | 14·28 | | | 13·77 | | | 12·19 | | | |
| East Center | 13·73 | | | 14·49 | | | 14·35 | | | 14·37 | | | 14·61 | | | |
| East | 8·97 | | | 8·91 | | | 8·09 | | | 7·86 | | | 7·06 | | | |
| Mediterranean | 10·13 | | | 11·70 | | | 13·33 | | | 14·39 | | | 16·55 | | | |
| North | 4·87 | | | 4·15 | | | 3·28 | | | 2·96 | | | 2·76 | | | |
| West | 14·34 | | | 14·29 | | | 14·90 | | | 15·58 | | | 15·48 | | | |
| Parisian area | 19·90 | | | 20·21 | | | 19·69 | | | 19·69 | | | 19·29 | | | |
| South West | 10·48 | | | 11·27 | | | 12·07 | | | 11·39 | | | 12·06 | | | |
| Smoking habits (%) | | | | | | | | | | | | | | | | 0·05 |
| Never smoker | 50·22 | | | 48·75 | | | 48·89 | | | 48·61 | | | 47·51 | | | |
| Former smoker | 36·43 | | | 39·79 | | | 40·73 | | | 41·76 | | | 43·60 | | | |
| Current smoker | 13·34 | | | 11·46 | | | 10·38 | | | 9·62 | | | 8·89 | | | |
| BMI (kg/m$^2$) | | 24·63 | 5·00 | | 24·48 | 4·77 | | 24·30 | 4·69 | | 24·10 | 4·47 | | 23·45 | 4·07 | < 0·0001 |

MEDI-LITE, literature-based adherence score to the Mediterranean diet; Q, quintiles.
* Values are means and standard deviation or %, as appropriate.
† *P*-values are based on linear contrast tests for continuous variables, and Mantel-Haenszel $\chi^2$ and $\chi^2$ tests for ordinal or categorical variables, respectively.

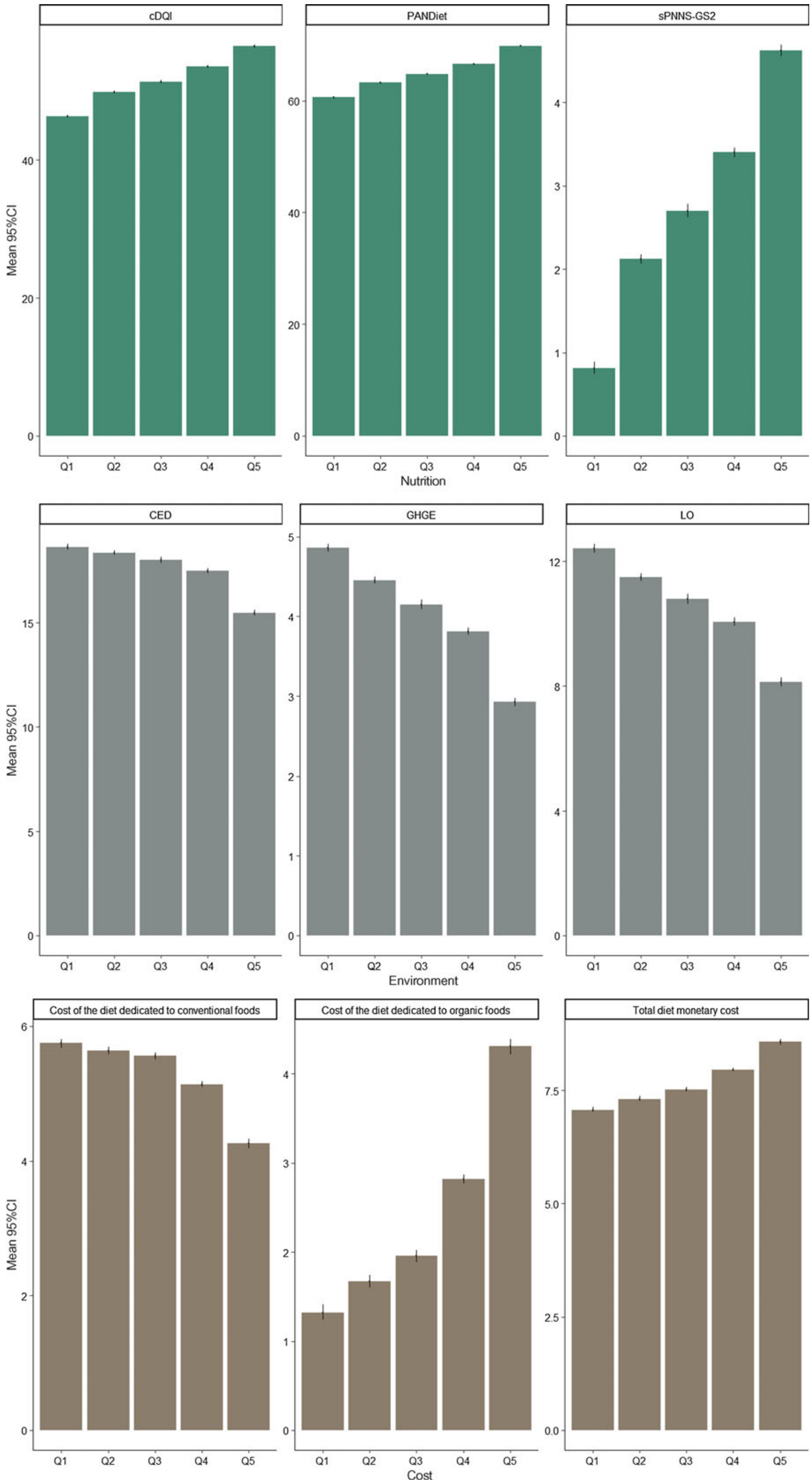


**Fig. 1.** Associations between adherence to the Mediterranean diet (MEDI-LITE) and diet sustainability indicators (mean and 95 % CI), *n* 29 210, 2014, NutriNet-Santé study[1,2]. cDQI, comprehensive diet quality index; CED, cumulative energy demand; GHGE, greenhouse gas emissions; LO, land occupation; MEDI-LITE, literature-based adherence score to the Mediterranean diet; PANDiet, Diet Quality Index Based on the Probability of Adequate Nutrient Intake; Q, quintiles; sPNNS-GS2, simplified Programme National Nutrition Santé-Guideline Score. cDQI, PANDIet and sPNNS-GS range from 0 to 85, 0 to 100, and -∞ to 14·25, respectively. CED, GHGE and LO are expressed in MJ/d, $kgCO_2eq$/d, $m^2$/d, respectively. Costs are expressed in €/d. [1]*P*-values are based on linear contrast tests. All *P*-values < 0·0001. [2]Model 2: adjusted for age, sex and daily energy intake.

had lower contribution to energy intake of SFA, and added sugars and higher contribution of MUFA, PUFA and carbohydrates. The intake of proteins from plant origin, fibre, and vitamins C and E were the highest in Q5 and the lowest in Q1. Adherence to the MEDI-LITE was negatively associated with the intake of vitamin $B_{12}$.

Table 3 presents the dietary exposure to different pesticides using the lower-bound scenario. In adjusted models, in line with the greater intakes of plant-based products in Q5 participants compared with Q1 participants (online Supplementary Table 2), higher levels of adherence to the MEDI-LITE were overall associated with higher pesticide exposure (higher values observed in the highest quintiles), except for chlorpropham for which the association was inverse and imidacloprid for which no association was observed.

### *Adherence to the Mediterranean diet and practices associated with the Mediterranean lifestyle*

The highest proportion of individuals with elevated physical activity was observed in Q5 (Table 4). Higher adherence to the MEDI-LITE was also related to higher organic food consumption (Q5 *v.* Q1: +171 %). Consumption of ready-to-use products decreased with adherence to the MEDI-LITE.

The results pertaining to the MDS are shown in online Supplementary Tables 4, 5, 6 and 7. Associations between diet sustainability and the MEDI-LITTE and the MDS per 1 SD are shown in online Supplementary Fig. 2. Overall, the same findings were observed. Further adjustment for education level did not substantially change the results (data not shown).

## Discussion

Using a multi-criteria analysis, the present study evaluated diet sustainability according to various levels of adherence to the Mediterranean diet, as reflected by the MEDI-LITE score, using a large adult sample from the NutriNet-Santé cohort.

Our evaluation encompassed various indicators including nutrient intakes, dietary scores, environmental pressures, monetary cost and dietary pesticide exposure. In this French adult population, following a Mediterranean dietary pattern was associated with nutritional and environmental benefits, although higher adherence was also accompanied by overall higher pesticide exposure and additional monetary costs.

To our knowledge, this is the first study which simultaneously considers all these indicators, in particular pesticide exposure, thus allowing a thorough evaluation of the sustainability of this dietary pattern.

The nutritional benefits of the Mediterranean diet have been extensively described. With regard to overall nutritional quality scores (reflecting both food- and nutrient-based recommendations) and nutrient intakes, our results are thus in line with those of previous studies[20], indicating a high nutritional quality associated with the adherence to the Mediterranean diet. These results are also in accordance with a work by Aboussaleh et al. which also reported that individuals following a Mediterranean diet more often met recommended nutrient and micronutrient intakes[48,49]. It should be noted that the recommended intake for alcohol in the Mediterranean diet is much higher than the official French national guideline[33].

In accordance with the literature, we observed that, in energy-adjusted models, higher adherence to the Mediterranean diet, as expressed by the MEDI-LITE, was associated with lower overall environmental impact (Q5 *v.* Q1: −40 %, −35, −17 %, for GHGE, LO and CED, respectively)[20]. Several studies conducted in other Mediterranean countries (Italy, Spain and Lebanon) have thus produced comparable findings[21,50–52]. This is explained by the fact that the Mediterranean diet encourages the consumption of plant-based foods, including fruit and vegetables, wholegrains, legumes and nuts, which exhibit lower overall environmental impacts than animal-based foods[19,36,53]. The carbon footprint of the Mediterranean diet has been extensively studied[20]. In adjusted models, total GHGE were 2·93 kg$CO_2$eq/d among high-adherent participants. In a study conducted in Spain, the Mediterranean diet was found to have GHGE levels in line with our findings (2·79 kg$CO_2$eq/d)[22]. Of note, the system boundaries considered in the Spanish study were not the same as ours. The value for GHGE for strong adherents to the Mediterranean diet in the present study is lower than that of omnivores (4·16 kg$CO_2$eq/d) but more than twice as high than that of vegans (1·17 kg$CO_2$eq/d) observed in a previous work that we carried out in the NutriNet-Santé cohort[54]. Our findings are partially in line with a simulation study performed on a global level[19]. Interestingly, energy adjustment appeared to reverse the relationships in the case of CED, emphasising that excessive energy intake is a strong contributor to overall environmental impact. In addition, the reduction in emissions is in line with the frugality aspect promoted by the Mediterranean lifestyle.

Regarding the economic dimension, we observed that participants reporting higher adherence to the Mediterranean diet exhibited slightly higher monetary costs than other groups (in energy-adjusted models). This is in line with some previous studies showing extra-cost associated with adherence to the Mediterranean diet pattern[21,55]. A study showed that following a Western diet was less expensive than following a Mediterranean diet[21]. In our study, participants who adhered the most to the Mediterranean diet spent 1·05€ extra per d. According to a recent systematic review, the Mediterranean diet is not more expensive than other diets but varies greatly (3·33 and 14·42€/ d per capita) according to the region, food brand, season and stores. In some cases, the costs can be the same as for other diets[20]. In the present work, individuals who adhered the most to the Mediterranean diet were also those who had higher intake of organic food, explaining the higher monetary cost. In our study, adjustment for energy intake tended to lower the cost difference, which is consistent with the findings of a work conducted in Spain comparing various dietary patterns[22]. In our analysis, we distinguished the prices of organic from conventional foods, and this may have led to higher diet monetary cost compared with other studies, in addition to methodological differences. The increase in monetary cost of 15 % for the highest adherence level raises a concern about affordability for the fraction of the population with limited incomes. Following the Mediterranean

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**Table 2.** Associations between adherence to the Mediterranean diet (MEDI-LITE) and nutrient intakes, *n* 29 210, 2014, NutriNet-Santé study

| | Quintiles of level of adherence to the Mediterranean diet | | | | | | | | | | | Per SD | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Q1 | | Q2 | | Q3 | | Q4 | | Q5 | | | | | |
| | Mean | 95 % CI | Mean | 95 % CI | Mean | 95 % CI | Mean | 95 % CI | Mean | 95 % CI | *P** | $\beta$ | 95 % CI | *P*† |
| Total energy intake (kcal/d) | | | | | | | | | | | | | | |
| Model 1‡ | 1759 | 1743, 1776 | 1891 | 1877, 1905 | 2002 | 1984, 2021 | 2111 | 2097, 2125 | 2250 | 2234, 2267 | < 0·0001 | 169·65 | 162·7, 176·6 | < 0·0001 |
| Model 2§ | 1765 | 1749, 1781 | 1893 | 1879, 1907 | 2003 | 1985, 2021 | 2108 | 2094, 2121 | 2246 | 2230, 2262 | < 0·0001 | 166·58 | 159·8, 173·4 | < 0·0001 |
| %Total fat | | | | | | | | | | | | | | |
| Model 1‡ | 41·11 | 40·93, 41·30 | 41·09 | 40·92, 41·25 | 40·98 | 40·76, 41·19 | 41·27 | 41·11, 41·44 | 41·63 | 41·44, 41·82 | < 0·0001 | 0·18 | 0·10, 0·27 | < 0·0001 |
| Model 2§ | 41·29 | 41·10, 41·48 | 41·10 | 40·94, 41·26 | 40·94 | 40·72, 41·15 | 41·20 | 41·04, 41·37 | 41·57 | 41·38, 41·76 | < 0·0001 | 0·1 | 0·02, 0·18 | 0·01 |
| %SFA | | | | | | | | | | | | | | |
| Model 1‡ | 16·62 | 16·53, 16·71 | 15·59 | 15·51, 15·67 | 14·95 | 14·85, 15·06 | 14·35 | 14·27, 14·43 | 13·01 | 12·92, 13·10 | < 0·0001 | –1·23 | –1·26, –1·19 | < 0·0001 |
| Model 2§ | 16·64 | 16·55, 16·73 | 15·59 | 15·51, 15·67 | 14·95 | 14·85, 15·06 | 14·34 | 14·26, 14·42 | 13·00 | 12·91, 13·09 | < 0·0001 | –1·24 | –1·28, –1·20 | < 0·0001 |
| %MUFA | | | | | | | | | | | | | | |
| Model 1‡ | 15·40 | 15·30, 15·51 | 15·98 | 15·89, 16·07 | 16·28 | 16·16, 16·40 | 16·76 | 16·67, 16·86 | 17·58 | 17·47, 17·69 | < 0·0001 | 0·75 | 0·70, 0·79 | < 0·0001 |
| Model 2§ | 15·48 | 15·38, 15·59 | 15·98 | 15·89, 16·08 | 16·26 | 16·14, 16·38 | 16·73 | 16·64, 16·83 | 17·56 | 17·45, 17·66 | < 0·0001 | 0·71 | 0·67, 0·76 | <. 0·0001 |
| %PUFA | | | | | | | | | | | | | | |
| Model 1‡ | 6·02 | 5·96, 6·09 | 6·44 | 6·39, 6·50 | 6·69 | 6·62, 6·76 | 7·09 | 7·04, 7·15 | 8 | 7·93, 8·07 | < 0·0001 | 0·67 | 0·64, 0·70 | < 0·0001 |
| Model 2§ | 6·08 | 6·01, 6·14 | 6·45 | 6·39, 6·50 | 6·68 | 6·60, 6·75 | 7·07 | 7·01, 7·13 | 7·98 | 7·91, 8·05 | < 0·0001 | 0·65 | 0·62, 0·68 | < 0·0001 |
| %Carbohydrates | | | | | | | | | | | | | | |
| Model 1‡ | 38·28 | 38·08, 38·48 | 39·09 | 38·92, 39·26 | 39·8 | 39·58, 40·03 | 40·06 | 39·88, 40·23 | 41 | 40·80, 41·20 | < 0·0001 | 0·93 | 0·85, 1·02 | < 0·0001 |
| Model 2§ | 38·00 | 37·80, 38·20 | 39·07 | 38·90, 39·24 | 39·86 | 39·64, 40·08 | 40·18 | 40·01, 40·35 | 41·12 | 40·92, 41·32 | < 0·0001 | 1·07 | 0·99, 1·16 | < 0·0001 |
| %Added sugars | | | | | | | | | | | | | | |
| Model 1‡ | 6·46 | 6·38, 6·54 | 5·58 | 5·51, 5·65 | 5·26 | 5·17, 5·36 | 4·89 | 4·82, 4·96 | 4·33 | 4·25, 4·42 | < 0·0001 | –0·73 | –0·76, –0·69 | < 0·0001 |
| Model 2§ | 6·32 | 6·24, 6·40 | 5·58 | 5·51, 5·64 | 5·29 | 5·20, 5·38 | 4·95 | 4·88, 5·02 | 4·39 | 4·30, 4·47 | < 0·0001 | –0·66 | –0·70, –0·63 | < 0·0001 |
| %Proteins | | | | | | | | | | | | | | |
| Model 1‡ | 20·2 | 20·11, 20·30 | 19·42 | 19·34, 19·50 | 18·82 | 18·72, 18·93 | 18·29 | 18·21, 18·37 | 17·01 | 16·91, 17·11 | < 0·0001 | –1·1 | –1·14, –1·06 | < 0·0001 |
| Model 2§ | 20·32 | 20·22, 20·41 | 19·43 | 19·35, 19·51 | 18·80 | 18·70, 18·91 | 18·24 | 18·16, 18·32 | 16·96 | 16·87, 17·06 | < 0·0001 | –1·16 | –1·20, –1·12 | < 0·0001 |
| Protein from plant origin (g/d) | | | | | | | | | | | | | | |
| Model 1‡ | 20·75 | 20·46, 21·03 | 24·68 | 24·43, 24·93 | 27·78 | 27·45, 28·10 | 31·4 | 31·14, 31·65 | 39·19 | 38·90, 39·48 | < 0·0001 | 6·29 | 6·17, 6·42 | < 0·0001 |
| Model 2‖ | 23·67 | 23·44, 23·90 | 26·07 | 25·87, 26·26 | 26·07 | 27·53, 28·04 | 30·06 | 29·86, 30·26 | 36·06 | 35·83, 36·29 | < 0·0001 | 4·22 | 4·13, 4·32 | < 0·0001 |
| Fibre (g/d) | | | | | | | | | | | | | | |
| Model 1‡ | 15·47 | 15·23, 15·72 | 19·97 | 19·76, 20·19 | 23·03 | 22·75, 23·30 | 26·23 | 26·02, 26·45 | 32·48 | 32·23, 32·73 | < 0·0001 | 5·8 | 5·69, 5·90 | < 0·0001 |
| Model 2‖ | 18·15 | 17·95, 18·36 | 21·10 | 20·92, 21·27 | 22·96 | 22·73, 23·19 | 25·02 | 24·84, 25·20 | 29·86 | 29·66, 30·07 | < 0·0001 | 3·98 | 3·89, 4·07 | < 0·0001 |
| PUFA (g/d) | | | | | | | | | | | | | | |
| Model 1‡ | 11·37 | 11·18, 11·57 | 13·12 | 12·95, 13·28 | 14·46 | 14·24, 14·68 | 16·13 | 15·96, 16·30 | 19·57 | 19·37, 19·76 | < 0·0001 | 2·79 | 2·71, 2·87 | < 0·0001 |
| Model 2‖ | 13·38 | 13·23, 13·53 | 13·99 | 13·86, 14·12 | 14·42 | 14·26, 14·59 | 15·22 | 15·09, 15·35 | 17·56 | 17·41, 17·71 | < 0·0001 | 1·41 | 1·35, 1·48 | < 0·0001 |
| *n*-3 fatty acids (g/d) | | | | | | | | | | | | | | |
| Model 1‡ | 1·38 | 1·35, 1·42 | 1·8 | 1·76, 1·83 | 2·04 | 2·00, 2·08 | 2·39 | 2·35, 2·42 | 3·03 | 3·00, 3·07 | < 0·0001 | 0·56 | 0·55, 0·58 | < 0·0001 |
| Model 2‖ | 1·69 | 1·66, 1·72 | 1·91 | 1·89, 1·94 | 2·03 | 1·99, 2·07 | 2·25 | 2·22, 2·28 | 2·75 | 2·72, 2·78 | < 0·0001 | 0·36 | 0·35, 0·37 | < 0·0001 |
| EPA (g/d) | | | | | | | | | | | | | | |
| Model 1‡ | 0·12 | 0·11, 0·12 | 0·17 | 0·17, 0·17 | 0·19 | 0·19, 0·20 | 0·23 | 0·22, 0·23 | 0·26 | 0·25, 0·26 | < 0·0001 | 0·05 | 0·05, 0·05 | < 0·0001 |
| Model 2‖ | 0·14 | 0·14, 0·15 | 0·18 | 0·18, 0·19 | 0·19 | 0·19, 0·20 | 0·21 | 0·21, 0·22 | 0·24 | 0·23, 0·24 | < 0·0001 | 0·0322 | 0·030, 0·034 | < 0·0001 |
| DHA (g/d) | | | | | | | | | | | | | | |
| Model 1‡ | 0·15 | 0·15, 0·16 | 0·22 | 0·22, 0·23 | 0·25 | 0·25, 0·26 | 0·29 | 0·29, 0·30 | 0·33 | 0·32, 0·33 | < 0·0001 | 0·06 | 0·06, 0·06 | < 0·0001 |
| Model 2‖ | 0·19 | 0·18, 0·19 | 0·24 | 0·23, 0·24 | 0·25 | 0·25, 0·26 | 0·28 | 0·27, 0·28 | 0·28 | 0·29, 0·30 | < 0·0001 | 0·04 | 0·04, 0·04 | < 0·0001 |
| Vitamin C (mg/d) | | | | | | | | | | | | | | |
| Model 1‡ | 108·3 | 106·0, 110·6 | 136·3 | 134·3, 138·2 | 156 | 153·4, 158·6 | 169·7 | 167·7, 171·7 | 194·3 | 192·0, 196·7 | < 0·0001 | 29·47 | 28·48, 30·45 | < 0·0001 |
| Model 2‖ | 123·6 | 121·4, 125·7 | 142·8 | 140·9, 144·6 | 155·6 | 153·2, 158·0 | 162·8 | 160·9, 164·7 | 179·3 | 177·1, 181·4 | < 0·0001 | 18·99 | 18·07, 19·91 | < 0·0001 |

**Table 2.** (*Continued*)

| | Quintiles of level of adherence to the Mediterranean diet | | | | | | | | | | | Per SD | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Q1 | | Q2 | | Q3 | | Q4 | | Q5 | | | | | |
| | Mean | 95 % CI | Mean | 95 % CI | Mean | 95 % CI | Mean | 95 % CI | Mean | 95 % CI | *P** | *β* | 95 % CI | *P*† |
| Vitamin E (mg/d) | | | | | | | | | | | | | | |
| Model 1‡ | 10·74 | 10·56, 10·91 | 12·83 | 12·68, 12·98 | 14·35 | 14·15, 14·54 | 16·01 | 15·85, 16·16 | 19·19 | 19·01, 19·36 | < 0·0001 | 2·88 | 2·81, 2·96 | < 0·0001 |
| Model 2‖ | 12·58 | 12·45, 12·72 | 13·61 | 13·49, 13·72 | 14·30 | 14·15, 14·45 | 15·17 | 15·06, 15·29 | 17·37 | 17·23, 17·51 | < 0·0001 | 1·62 | 1·56, 1·68 | < 0·0001 |
| Vitamin $B_{12}$ (mg/d) | | | | | | | | | | | | | | |
| Model 1‡ | 5·83 | 5·68, 5·97 | 6·44 | 6·31, 6·57 | 6·61 | 6·44, 6·78 | 6·94 | 6·81, 7·07 | 6·63 | 6·48, 6·78 | < 0·0001 | 0·27 | 0·21, 0·33 | < 0·0001 |
| Model 2‖ | 6·84 | 6·71, 6·98 | 6·84 | 6·73, 6·96 | 6·57 | 6·42, 6·73 | 6·48 | 6·36, 6·60 | 5·68 | 5·55, 5·82 | < 0·0001 | −0·42 | −0·47, −0·36 | < 0·0001 |
| Ca (mg/d) | | | | | | | | | | | | | | |
| Model 1‡ | 1100 | 1088, 1112 | 1113 | 1102, 1123 | 1125 | 1112, 1139 | 1133 | 1123, 1144 | 1101 | 1089, 1113 | 0·24 | 0·28 | −4·88, 5·45 | 0·91 |
| Model 2‖ | 1223 | 1214, 1231 | 1166 | 1159, 1173 | 1123 | 1114, 1133 | 1078 | 1071, 1085 | 978 | 970, 987 | < 0·0001 | −84·76 | −88·4, −81·1 | < 0·0001 |
| Ethanol (g/d) | | | | | | | | | | | | | | |
| Model 1‡ | 9 | 8·67, 9·34 | 8·54 | 8·25, 8·83 | 8·44 | 8·06, 8·82 | 8·5 | 8·21, 8·79 | 8·07 | 7·73, 8·41 | 0·0003 | −0·22 | −0·37, −0·08 | < 0·0001 |
| Model 2‖ | 10·78 | 10·47, 11·09 | 9·15 | 8·89, 9·42 | 8·35 | 8·01, 8·70 | 7·68 | 7·42, 7·95 | 6·57 | 6·26, 6·88 | < 0·0001 | −1·36 | −1·50, −1·23 | < 0·0001 |

MEDI-LITE, literature-based adherence score to the Mediterranean diet; Q, quintiles.
* *P*-values are based on linear contrast tests.
† *P*-values are calculated by linear regression.
‡Model 1: unadjusted.
§Model 2: adjusted for age and sex.
‖ Model 2: adjusted for age, sex and daily energy intake using the residual method[47].

**Table 3.** Associations between adherence to the Mediterranean diet (MEDI-LITE) and dietary exposure to pesticides (μg/kg bw/day) from plant-based foods, *n* 29 210, 2014, NutriNet-Santé study

| | Quintiles of level of adherence to the Mediterranean diet | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Q1 | | Q2 | | Q3 | | Q4 | | Q5 | | | Per SD | | |
| | Mean | 95 % CI | Mean | 95 % CI | Mean | 95 % CI | Mean | 95 % CI | Mean | 95 % CI | *P** | *β* | 95 % CI | *P*† |
| Acetamiprid | | | | | | | | | | | | | | |
| Model 1‡ | 0·042 | 0·0402, 0·0438 | 0·0481 | 0·0465, 0·0496 | 0·0536 | 0·0516, 0·0557 | 0·0538 | 0·0522, 0·0553 | 0·0518 | 0·0500, 0·0536 | < 0·0001 | 0·0037 | 0·0030, 0·0045 | < 0·0001 |
| Model 2§ | 0·0437 | 0·0419, 0·0455 | 0·0484 | 0·0469, 0·0499 | 0·0533 | 0·0513, 0·0553 | 0·0531 | 0·0515, 0·0546 | 0·0508 | 0·0490, 0·0526 | < 0·0001 | 0·0028 | 0·0020, 0·0036 | < 0·0001 |
| Anthraquinone | | | | | | | | | | | | | | |
| Model 1‡ | 0·0005 | 0·0005, 0·0006 | 0·0006 | 0·0005, 0·0006 | 0·0006 | 0·0005, 0·0006 | 0·0006 | 0·0006, 0·0007 | 0·0007 | 0·0006, 0·0007 | < 0·0001 | 0 | 0·0000, 0·0001 | < 0·0001 |
| Model 2§ | 0·0005 | 0·0005, 0·0006 | 0·0006 | 0·0005, 0·0006 | 0·0006 | 0·0006, 0·0006 | 0·0006 | 0·0006, 0·0006 | 0·0006 | 0·0006, 0·0007 | 0·003 | 0 | 0·0000, 0·0000 | 0·006 |
| Azadirachtin | | | | | | | | | | | | | | |
| Model 1‡ | 0·0002 | 0·0001, 0·0002 | 0·0003 | 0·0002, 0·0003 | 0·0003 | 0·0003, 0·0003 | 0·0004 | 0·0004, 0·0004 | 0·0006 | 0·0006, 0·0006 | < 0·0001 | 0·0001 | 0·0001, 0·0002 | < 0·0001 |
| Model 2§ | 0·0002 | 0·0002, 0·0002 | 0·0003 | 0·0003, 0·0003 | 0·0003 | 0·0003, 0·0003 | 0·0004 | 0·0004, 0·0004 | 0·0006 | 0·0006, 0·0006 | < 0·0001 | 0·0001 | 0·0001, 0·0001 | < 0·0001 |
| Azoxystrobin | | | | | | | | | | | | | | |
| Model 1‡ | 0·0311 | 0·0298, 0·0323 | 0·0399 | 0·0388, 0·0409 | 0·0447 | 0·0433, 0·0461 | 0·0482 | 0·0471, 0·0493 | 0·0495 | 0·0482, 0·0508 | < 0·0001 | 0·0064 | 0·0058, 0·0069 | < 0·0001 |
| Model 2§ | 0·0351 | 0·0338, 0·0364 | 0·0415 | 0·0404, 0·0425 | 0·0446 | 0·0432, 0·0460 | 0·0464 | 0·0453, 0·0475 | 0·0457 | 0·0444, 0·0469 | < 0·0001 | 0·0036 | 0·0031, 0·0042 | < 0·0001 |
| Boscalid | | | | | | | | | | | | | | |
| Model 1‡ | 0·0767 | 0·0740, 0·0795 | 0·1069 | 0·1045, 0·1093 | 0·1222 | 0·1191, 0·1254 | 0·1323 | 0·1298, 0·1347 | 0·1325 | 0·1297, 0·1353 | < 0·0001 | 0·0194 | 0·0182, 0·0206 | < 0·0001 |
| Model 2§ | 0·0909 | 0·0882, 0·0936 | 0·1116 | 0·1093, 0·1139 | 0·1212 | 0·1181, 0·1242 | 0·126 | 0·1236, 0·1283 | 0·1208 | 0·1181, 0·1235 | < 0·0001 | 0·0104 | 0·0092, 0·0116 | < 0·0001 |
| Carbendazim | | | | | | | | | | | | | | |
| Model 1‡ | 0·0397 | 0·0384, 0·0411 | 0·0459 | 0·0447, 0·0471 | 0·0508 | 0·0492, 0·0523 | 0·052 | 0·0508, 0·0532 | 0·0529 | 0·0515, 0·0543 | < 0·0001 | 0·0047 | 0·0041, 0·0053 | < 0·0001 |
| Model 2§ | 0·0413 | 0·0399, 0·0426 | 0·0463 | 0·0451, 0·0475 | 0·0506 | 0·0490, 0·0521 | 0·0513 | 0·0502, 0·0525 | 0·0517 | 0·0503, 0·0531 | < 0·0001 | 0·0038 | 0·0032, 0·0044 | < 0·0001 |
| Chlorpropham | | | | | | | | | | | | | | |
| Model 1‡ | 0·057 | 0·0553, 0·0588 | 0·0616 | 0·0601, 0·0632 | 0·064 | 0·0620, 0·0659 | 0·0669 | 0·0654, 0·0685 | 0·0619 | 0·0601, 0·0636 | < 0·0001 | 0·0018 | 0·0011, 0·0026 | < 0·0001 |
| Model 2§ | 0·0653 | 0·0636, 0·0670 | 0·065 | 0·0636, 0·0665 | 0·0637 | 0·0618, 0·0656 | 0·0632 | 0·0617, 0·0646 | 0·054 | 0·0522, 0·0557 | < 0·0001 | –0·0039 | –0·005, –0·003 | < 0·0001 |
| Chlorpyrifos | | | | | | | | | | | | | | |
| Model 1‡ | 0·0512 | 0·0497, 0·0528 | 0·0627 | 0·0614, 0·0641 | 0·0698 | 0·0680, 0·0716 | 0·0709 | 0·0695, 0·0723 | 0·0701 | 0·0685, 0·0717 | < 0·0001 | 0·0066 | 0·0059, 0·0073 | < 0·0001 |
| Model 2§ | 0·0552 | 0·0537, 0·0568 | 0·064 | 0·0627, 0·0653 | 0·0694 | 0·0677, 0·0711 | 0·0692 | 0·0678, 0·0705 | 0·0668 | 0·0652, 0·0684 | < 0·0001 | 0·0041 | 0·0034, 0·0048 | < 0·0001 |
| Lambda Cyhalothrin | | | | | | | | | | | | | | |
| Model 1‡ | 0·0065 | 0·0062, 0·0067 | 0·0092 | 0·0090, 0·0094 | 0·0105 | 0·0102, 0·0108 | 0·0112 | 0·0109, 0·0114 | 0·0113 | 0·0110, 0·0115 | < 0·0001 | 0·0016 | 0·0015, 0·0017 | < 0·0001 |
| Model 2§ | 0·0077 | 0·0074, 0·0079 | 0·0096 | 0·0094, 0·0098 | 0·0104 | 0·0102, 0·0107 | 0·0107 | 0·0104, 0·0109 | 0·0103 | 0·0100, 0·0105 | < 0·0001 | 0·0009 | 0·0008, 0·0010 | < 0·0001 |
| Cypermethrin | | | | | | | | | | | | | | |
| Model 1‡ | 0·0616 | 0·0591, 0·0642 | 0·0702 | 0·0680, 0·0724 | 0·078 | 0·0751, 0·0809 | 0·0793 | 0·0770, 0·0815 | 0·0804 | 0·0778, 0·0830 | < 0·0001 | 0·0069 | 0·0058, 0·0080 | < 0·0001 |
| Model 2§ | 0·0633 | 0·0607, 0·0659 | 0·0705 | 0·0683, 0·0726 | 0·0777 | 0·0748, 0·0805 | 0·0786 | 0·0764, 0·0809 | 0·0794 | 0·0768, 0·0820 | < 0·0001 | 0·006 | 0·0048, 0·0071 | < 0·0001 |
| Cyprodinil | | | | | | | | | | | | | | |
| Model 1‡ | 0·0467 | 0·0447, 0·0488 | 0·0663 | 0·0645, 0·0681 | 0·0747 | 0·0724, 0·0770 | 0·0799 | 0·0781, 0·0817 | 0·0789 | 0·0768, 0·0810 | < 0·0001 | 0·0112 | 0·0103, 0·0120 | < 0·0001 |
| Model 2§ | 0·0563 | 0·0543, 0·0583 | 0·0694 | 0·0677, 0·0711 | 0·0739 | 0·0717, 0·0762 | 0·0757 | 0·0740, 0·0774 | 0·0711 | 0·0691, 0·0731 | < 0·0001 | 0·0051 | 0·0042, 0·0060 | < 0·0001 |
| Difenoconazole | | | | | | | | | | | | | | |
| Model 1‡ | 0·0115 | 0·0111, 0·0120 | 0·0152 | 0·0149, 0·0156 | 0·0172 | 0·0167, 0·0177 | 0·0189 | 0·0185, 0·0193 | 0·0196 | 0·0192, 0·0201 | < 0·0001 | 0·0028 | 0·0026, 0·0030 | < 0·0001 |
| Model 2§ | 0·0131 | 0·0127, 0·0135 | 0·0157 | 0·0154, 0·0161 | 0·0171 | 0·0166, 0·0176 | 0·0182 | 0·0179, 0·0186 | 0·0183 | 0·0179, 0·0188 | < 0·0001 | 0·0018 | 0·0016, 0·0020 | < 0·0001 |
| Dimethoate Ometoate | | | | | | | | | | | | | | |
| Model 1‡ | 0·0024 | 0·0023, 0·0025 | 0·003 | 0·0029, 0·0031 | 0·0034 | 0·0033, 0·0035 | 0·0035 | 0·0034, 0·0036 | 0·0036 | 0·0035, 0·0037 | < 0·0001 | 0·0004 | 0·0004, 0·0004 | < 0·0001 |
| Model 2§ | 0·0027 | 0·0026, 0·0028 | 0·0031 | 0·0030, 0·0032 | 0·0034 | 0·0033, 0·0035 | 0·0034 | 0·0033, 0·0035 | 0·0034 | 0·0033, 0·0035 | < 0·0001 | 0·0002 | 0·0002, 0·0003 | < 0·0001 |
| Fenhexamid | | | | | | | | | | | | | | |
| Model 1‡ | 0·0639 | 0·0605, 0·0673 | 0·0866 | 0·0837, 0·0895 | 0·0984 | 0·0946, 0·1023 | 0·1032 | 0·1003, 0·1062 | 0·0975 | 0·0941, 0·1009 | < 0·0001 | 0·0121 | 0·0106, 0·0135 | < 0·0001 |
| Model 2§ | 0·0764 | 0·0730, 0·0797 | 0·0905 | 0·0876, 0·0934 | 0·0974 | 0·0936, 0·1011 | 0·0977 | 0·0948, 0·1006 | 0·0876 | 0·0842, 0·0910 | < 0·0001 | 0·0043 | 0·0028, 0·0058 | < 0·0001 |
| Glyphosate | | | | | | | | | | | | | | |
| Model 1‡ | 0·0019 | 0·0017, 0·0020 | 0·0026 | 0·0025, 0·0027 | 0·0034 | 0·0032, 0·0035 | 0·0042 | 0·0041, 0·0043 | 0·0057 | 0·0056, 0·0058 | < 0·0001 | 0·0013 | 0·0012, 0·0013 | < 0·0001 |
| Model 2§ | 0·0021 | 0·0020, 0·0022 | 0·0027 | 0·0026, 0·0028 | 0·0034 | 0·0032, 0·0035 | 0·0041 | 0·0040, 0·0042 | 0·0054 | 0·0053, 0·0056 | < 0·0001 | 0·0011 | 0·0011, 0·0012 | < 0·0001 |

**Table 3.** (*Continued*)

| | Quintiles of level of adherence to the Mediterranean diet | | | | | | | | | | | Per SD | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Q1 | | Q2 | | Q3 | | Q4 | | Q5 | | | | | |
| | Mean | 95 % CI | Mean | 95 % CI | Mean | 95 % CI | Mean | 95 % CI | Mean | 95 % CI | *P** | $\beta$ | 95 % CI | *P*† |
| Imazalil | | | | | | | | | | | | | | |
| Model 1‡ | 0·5605 | 0·5361, 0·5848 | 0·7209 | 0·6999, 0·7419 | 0·8143 | 0·7867, 0·8420 | 0·8317 | 0·8104, 0·8531 | 0·8039 | 0·7793, 0·8285 | < 0·0001 | 0·0846 | 0·0741, 0·0951 | < 0·0001 |
| Model 2§ | 0·6315 | 0·6070, 0·6560 | 0·7454 | 0·7246, 0·7662 | 0·8094 | 0·7821, 0·8366 | 0·8003 | 0·7792, 0·8215 | 0·7433 | 0·7186, 0·7679 | < 0·0001 | 0·0386 | 0·0278, 0·0495 | < 0·0001 |
| Imidacloprid | | | | | | | | | | | | | | |
| Model 1‡ | 0·0741 | 0·0721, 0·0760 | 0·0768 | 0·0751, 0·0785 | 0·0822 | 0·0800, 0·0845 | 0·0802 | 0·0785, 0·0819 | 0·0791 | 0·0772, 0·0811 | < 0·0001 | 0·002 | 0·0012, 0·0029 | < 0·0001 |
| Model 2§ | 0·0773 | 0·0753, 0·0792 | 0·0787 | 0·0771, 0·0804 | 0·0824 | 0·0802, 0·0846 | 0·0788 | 0·0771, 0·0805 | 0·075 | 0·0730, 0·0770 | 0·15 | –0·0005 | –0·001, 0·0004 | 0·25 |
| Iprodione | | | | | | | | | | | | | | |
| Model 1‡ | 0·081 | 0·0768, 0·0851 | 0·1227 | 0·1191, 0·1263 | 0·143 | 0·1383, 0·1477 | 0·152 | 0·1483, 0·1556 | 0·1516 | 0·1474, 0·1558 | < 0·0001 | 0·0241 | 0·0223, 0·0259 | < 0·0001 |
| Model 2§ | 0·1008 | 0·0967, 0·1049 | 0·1287 | 0·1252, 0·1322 | 0·1412 | 0·1367, 0·1458 | 0·1432 | 0·1397, 0·1468 | 0·136 | 0·1319, 0·1401 | < 0·0001 | 0·0117 | 0·0099, 0·0135 | < 0·0001 |
| Pyrethrins | | | | | | | | | | | | | | |
| Model 1‡ | 0·0017 | 0·0016, 0·0017 | 0·0019 | 0·0018, 0·0019 | 0·0021 | 0·0020, 0·0021 | 0·0023 | 0·0023, 0·0024 | 0·0026 | 0·0026, 0·0027 | < 0·0001 | 0·0003 | 0·0003, 0·0004 | < 0·0001 |
| Model 2§ | 0·0018 | 0·0017, 0·0018 | 0·0019 | 0·0019, 0·0020 | 0·0021 | 0·0020, 0·0022 | 0·0023 | 0·0022, 0·0023 | 0·0025 | 0·0025, 0·0026 | < 0·0001 | 0·0003 | 0·0003, 0·0003 | < 0·0001 |
| Spinosad | | | | | | | | | | | | | | |
| Model 1‡ | 0·0736 | 0·0692, 0·0779 | 0·1105 | 0·1068, 0·1143 | 0·1377 | 0·1328, 0·1426 | 0·1612 | 0·1574, 0·1650 | 0·2214 | 0·2171, 0·2258 | < 0·0001 | 0·0507 | 0·0489, 0·0526 | < 0·0001 |
| Model 2§ | 0·0818 | 0·0774, 0·0861 | 0·1124 | 0·1087, 0·1161 | 0·1365 | 0·1317, 0·1414 | 0·1577 | 0·1540, 0·1615 | 0·216 | 0·2117, 0·2204 | < 0·0001 | 0·0464 | 0·0445, 0·0483 | < 0·0001 |
| Tebuconazole | | | | | | | | | | | | | | |
| Model 1‡ | 0·0206 | 0·0196, 0·0217 | 0·0302 | 0·0293, 0·0311 | 0·0354 | 0·0342, 0·0366 | 0·0368 | 0·0359, 0·0378 | 0·0365 | 0·0355, 0·0376 | < 0·0001 | 0·0054 | 0·0050, 0·0059 | < 0·0001 |
| Model 2§ | 0·0257 | 0·0247, 0·0268 | 0·0318 | 0·0309, 0·0327 | 0·035 | 0·0338, 0·0361 | 0·0346 | 0·0337, 0·0355 | 0·0324 | 0·0314, 0·0335 | < 0·0001 | 0·0022 | 0·0017, 0·0027 | < 0·0001 |
| Thiabendazole | | | | | | | | | | | | | | |
| Model 1‡ | 0·219 | 0·2112, 0·2268 | 0·2604 | 0·2537, 0·2672 | 0·289 | 0·2801, 0·2979 | 0·2912 | 0·2843, 0·2981 | 0·2802 | 0·2723, 0·2881 | < 0·0001 | 0·0216 | 0·0182, 0·0250 | < 0·0001 |
| Model 2§ | 0·2412 | 0·2333, 0·2491 | 0·2693 | 0·2626, 0·2760 | 0·2881 | 0·2794, 0·2969 | 0·2813 | 0·2745, 0·2881 | 0·2591 | 0·2512, 0·2670 | 0·0002 | 0·0065 | 0·0030, 0·0100 | 0·0003 |

MEDI-LITE, literature-based adherence score to the Mediterranean diet; Q, quintiles.
* *P*-values are based on linear contrast tests.
† *P*-values are calculated by linear regression.
‡ Model 1: unadjusted.
§ Model 2: adjusted for age, sex and daily energy intake.

**Table 4.** Associations between adherence to the Mediterranean diet (MEDI-LITE) and lifestyle and eating practices associated with the Mediterranean lifestyle, *n* 29 210, 2014, NutriNet-Santé study*

| | Quintiles of level of adherence to the Mediterranean diet | | | | | | | | | | | | | | | Per SD | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Q1 | | | Q2 | | | Q3 | | | Q4 | | | Q5 | | | | | | |
| | % | Mean | 95 % CI | % | Mean | 95 % CI | % | Mean | 95 % CI | % | Mean | 95 % CI | % | Mean | 95 % CI | *P*† | *β* | 95 % CI | *P*‡ |
| Physical activity (%) | | | | | | | | | | | | | | | | | | | |
| Model 1§ | | | | | | | | | | | | | | | | < 0·0001 | | | |
| Missing data | 11·90 | | | 10·68 | | | 11·09 | | | 10·83 | | | 9·44 | | | | | | |
| Low | 26·12 | | | 21·71 | | | 18·52 | | | 16·28 | | | 13·12 | | | | | | |
| Moderate | 35·62 | | | 35·67 | | | 35·73 | | | 37·21 | | | 37·54 | | | | | | |
| High | 26·36 | | | 31·94 | | | 34·66 | | | 35·68 | | | 39·90 | | | | | | |
| Model 2‖ | | | | | | | | | | | | | | | | < 0·0001 | | | |
| Missing data | 11·66 | | | 10·29 | | | 10·61 | | | 10·31 | | | 8·91 | | | | | | |
| Low | 24·74 | | | 21·21 | | | 18·31 | | | 16·33 | | | 13·17 | | | | | | |
| Moderate | 34·17 | | | 35·04 | | | 35·59 | | | 37·65 | | | 38·29 | | | | | | |
| High | 29·43 | | | 33·46 | | | 35·49 | | | 35·71 | | | 39·63 | | | | | | |
| Organic food consumption | | | | | | | | | | | | | | | | | | | |
| Model 1§ | | 0·18 | 0·17, 0·18 | | 0·24 | 0·24, 0·25 | | 0·28 | 0·27, 0·29 | | 0·33 | 0·33, 0·34 | | 0·45 | 0·45, 0·46 | < 0·0001 | 0·09 | 0·09, 0·10 | < 0·0001 |
| Model 2‖ | | 0·17 | 0·16, 0·17 | | 0·24 | 0·23, 0·24 | | 0·28 | 0·27, 0·29 | | 0·34 | 0·33, 0·34 | | 0·46 | 0·46, 0·47 | < 0·0001 | 0·10 | 0·10, 0·10 | < 0·0001 |
| Consumption of ready-to-use products¶ | | | | | | | | | | | | | | | | | | | |
| Model 1§ | | 1·27 | 1·25, 1·28 | | 1·21 | 1·20, 1·22 | | 1·19 | 1·18, 1·21 | | 1·17 | 1·16, 1·18 | | 1·09 | 1·08, 1·10 | < 0·0001 | –0·06 | –0·06, –0·05 | < 0·0001 |
| Model 2‖ | | 1·28 | 1·27, 1·29 | | 1·22 | 1·21, 1·23 | | 1·19 | 1·18, 1·21 | | 1·16 | 1·15, 1·17 | | 1·07 | 1·06, 1·08 | < 0·0001 | –0·07 | –0·08, –0·07 | < 0·0001 |

MEDI-LITE, literature-based adherence score to the Mediterranean diet; Q, quintiles.
* Values are means (95 % CI) or %, as appropriate.
† *P*-values are based on Mantel-Haenszel $\chi^2$ tests or linear contrast tests, as appropriate.
‡ *P*-values are calculated by linear regression.
§ Model 1: unadjusted.
‖ Model 2: adjusted for age, sex and daily energy intake.
¶ For the consumption of ready-to-use products: *n* 29 177.

diet was approximately 1€/d more expensive. Although this value is an estimate and does not represent the actual cost difference, this difference still reflects food inequality. One euro per d may constitute a substantial burden for disadvantaged households. For instance, in an intervention study carried out in a socially deprived districts of Marseille (France), individuals spent on average 3·65€/d per person for food consumed at home[56]. This should encourage national authorities to subsidise environmentally sustainable and healthy diets such as the Mediterranean diet to allow as many people as possible to access this diet and benefit from the reduced environmental and health impacts associated with it. The Mediterranean diet has been described as a sustainable diet by several conceptual studies[57–59]. However, safety aspects are rarely considered, and few studies have investigated pesticide exposure associated with adherence to the Mediterranean diet. It is known that plant foods are the most contaminated food groups by pesticide residues, while organic plant foods are less contaminated than their conventional counterparts[60]. In the present work, due to their greater consumption of cereals, fruits and vegetables, participants in highest quintiles were more exposed to pesticide residues than individuals in lowest quintiles (Q1 and Q2). Thus, intakes of less pesticide-contaminated organically grown foods did not appear to fully compensate for the higher exposure from high intake of conventional foods of plant origin among these participants. In contrast, another study based on the NutriNet-Santé cohort showed that individuals with a very high contribution of organic food in their diet (on average 70 % of food coming from organic sources) had a reduced exposure to food pesticide residues compared with individuals with null or low contribution of organic food in the diet[42]. The higher discrimination between the two extreme quintiles in terms of share of organic in the diet (71 % (Q5) *v.* 0 % (Q1)) in the latter study as compared in the present study (46 % *v.* 17 %) also explains the differences regarding pesticide exposure between the two studies. It was also observed during a controlled trial that a Mediterranean diet combined with full organic food intake reduced total pesticides exposure by > 90 %, while increasing conventional fruit and vegetable consumption led to higher levels of pesticide exposure[61]. In a recent study carried out in the USA, consumption of certain foods, such as legumes and grains, was the primary contributor to total dietary glyphosate body burden rather than diet style (Mediterranean-style and Vegetarian eating pattern)[62]. Pesticide exposure through diet in the general population has been associated with adverse health outcomes[7,8]. In a recent US study based on three large adult cohorts, a diet rich in low-pesticide contaminated fruit and vegetables reduced mortality, whereas a comparable diet with high-pesticide contaminated fruit and vegetables had no longer a significant protective effect[6]. However, the healthiness of the Mediterranean diet probably outweighs the potential deleterious effect of the exposure to pesticides, given the very large literature showing its possible health benefits[16], although more data are needed to quantify this precisely. Particular attention should also be paid to seafood, since these products are source of contamination of persistent organic pollutants, furans or polychlorinated biphenyls[63]. This is of importance and needs further consideration since sustainable diets, as defined by the FAO, are supposed to provide 'safe foods'[11]. This indicates the need to generalise production methods limiting agricultural inputs to maximise the health benefits of plant-rich diets such as the Mediterranean diet. A recent study conducted in Australia somewhat supports this idea[64]. In this study, a dietary shift towards recommended dietary patterns was associated with a higher environmental pesticide toxicity footprint, leading the authors to conclude that actions in the agricultural sector might the best approach to reduce the environmental burden associated with pesticides.

We also examined the associations between adherence to the Mediterranean diet and other components of the Mediterranean lifestyle (apart from the diet composition). We observed that individuals who adhered to the Mediterranean diet were more often physically active and less often prone to eat ready-to-use products and therefore more likely to have varied culinary and cooking practices. Furthermore, the Mediterranean diet now also emphasises the importance of eco-friendly products[15]. We observed here a strong positive association between organic food consumption and adherence to the Mediterranean diet which is of interest since organic food consumption has been associated with biodiversity benefits[65]. Therefore, individuals who followed Mediterranean dietary patterns appeared to be more likely to also follow the principles of a Mediterranean lifestyle, thereby increasing possible health benefit.

Some limitations should be noted. First, the NutriNet-Santé cohort study includes volunteers, who are probably more interested in nutrition and health issues than the general population, leading to a health-conscious sample with healthier eating habits and probably higher adherence to the Mediterranean diet than the French adult population[66]. It has also been shown that NutriNet-Santé participants tend to exhibit a higher socioeconomic status than the general population[67]. It is likely that some population subgroups, such as deprived individuals or individuals who are not-Internet users (e.g. computer illiteracy), are not included or underrepresented in the cohort. Therefore, caution is needed before generalising the results to the French population. Moreover, food consumption data were self-reported using a FFQ, making some degree of measurement error inevitable. Total food intake may have thus been overestimated[68], and possibly a desirability bias may have occurred. Furthermore, the questions used to estimate the share of organic food in the diet had not been validated. Nonetheless, the original FFQ used to develop the Org-FFQ has been validated against dietary records[27], and all lifestyle and anthropometric questionnaires have been validated against traditional methods[69,70]. In addition, fish is one of the most important beneficial components of the Mediterranean diet but while we did not have the most relevant indicators to assess its environmental impact, we do know that 60 % of fish stocks are fully exploited and 30 % overexploited[2]. Regarding environmental indicators, biodiversity and water use should be also accounted for in future studies, in particular due to the high water footprint of some products such as nuts[71], for which we had very limited data. Furthermore, we only assessed pesticide exposure through foods of plant origin since they are the primary contributors. However, we may have underestimated the overall pesticide impact, in particular among participants eating more animal-based foods. In addition, we did not consider potential nutritional differences between organic and conventional products due to lack of data. Lastly, dietary data and related sustainability outcomes were collected in 2014, almost 10 years ago, and the food system has been through and is still going through multiple crises (including COVID-19 pandemic, the massive acceleration of climate change, invasion of Ukraine and inflation). As a result – more than dietary patterns themselves which are relatively constant over time – diet-related costs observed in the current study do not reflect the current situation (e.g. inflation and reduction of organic purchase among low-income households). Similarly, pesticide exposure patterns may have changed since 2014 (e.g. ban of certain molecules and introduction of new ones). However, overall, the extent of food sample contaminations did not noticeably change during this time period[41,60]. Our study has also several strengths. This is the first study to concomitantly consider multiple criteria (using a wide range of indicators related to sustainability) and describe the pesticide exposure in relation to Mediterranean diet sustainability. In addition, we were able to distinguish organic from conventional food intakes. We also attempted to account for the other principles of the Mediterranean lifestyle. Finally, our study was based on a large sample allowing an important diversity of dietary patterns and profiles.

### Conclusions

In this population of French adults, adherence to the Mediterranean diet was associated with higher nutritional quality and overall lower environmental impact. However, adherence to the Mediterranean diet (based on high intake of foods from plant origin) was overall positively associated with pesticide residue exposure which was not fully counterbalanced by the higher consumption of organic food. This underscores the importance of implementing political strategies aiming to generalise production methods limiting pesticide residue exposure. The higher monetary cost may also be a barrier for acceptance and highlights the urgent need for strategies aiming to promote affordable, nutritious but also safe and environmentally sustainable diets for all.

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The authors' responsibilities were as follows: J. Bau., D. L., B. A., B. L., S. H., P. P. and E. K-G. led the BioNutriNet project from which the data used came; D. L., B. A., B. L., J. Br., F. B., I. D., M. T., S. H., M-J. A., P. P. and E. K-G. contributed to interpretation of results and provided critical revisions to the manuscript; J. Bau. and F. N. performed statistical analysis, wrote the paper and had full access to all the data in the study; J. Bau. had primary responsibility for the final content and took responsibility for the integrity of the data and the accuracy of the data analysis as guarantor; and all authors read and approved the final manuscript.

There are no conflicts of interest.

## Supplementary material

For supplementary material/s referred to in this article, please visit https://doi.org/10.1017/S0007114523001411

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