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The Mediterranean diet as a potential strategy for mitigating the intake and exposure to contaminants resulting from food processing

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A B S T R A C T

Dietary intake represents a significant route of exposure to chemical contaminants, including compounds formed during the food processing. The present study estimated the intake and exposure to 11 food contaminants in adults with metabolic syndrome. The changes during a Mediterranean diet (MedDiet) based intervention were also evaluated. The present investigation included 225 participants from one of the Málaga centers of the PREDIMED-Plus trial (2013–2016). The dietary intake was assessed through the implementation of a validated food frequency questionnaire, and adherence to the Mediterranean diet was determined using a screener tool comprising 17 items. Contaminant concentrations were obtained from the CONT11 database and linked to reported food consumption. The findings, based on an average follow-up period of two years, revealed a decline in both weight and body mass index, with a simultaneous increase in adherence to the MedDiet. The intervention arm exhibited a more pronounced enhancement in adherence to MedDiet. The estimated intake and exposure of most contaminants declined, except for nitrates and total polycyclic aromatic hydrocarbons, which increased. Furosine, pyrraline and Amadori compounds were directly associated with body mass index and waist circumference, while MedDiet adherence was inversely associated with estimated exposure to these contaminants. These findings are consistent with the hypothesis that a dietary intervention focused on MedDiet may reduce estimated dietary exposure to several contaminants derived from processing, while simultaneously improving anthropometric outcomes. Notwithstanding the necessity for future

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validation of these estimates against biomarkers, this scalable approach is especially well suited to nutritional epidemiology in large cohorts.

1. Introduction

The Mediterranean Diet (MedDiet) is widely regarded as one of the most nutritionally and health-promoting diets globally [1–3]. The MedDiet is characterized by the abundant intake of fruits, vegetables, legumes, whole grain cereals, nuts, seeds and olive oil, as well as the regular consumption of fish or seafood and low intake of red and processed meat and sweets [4]. In other words, it is a balanced diet that provides a large number of nutrients that have a protective effect on health.

Diet is the primary source of exposure to certain contaminants [5]. Dietary contaminants may come from different origins of the farm-to-fork axis, including environmental contamination, such as the employment of pesticides in agricultural practices or the transportation of alimentary products, as well as intrinsic factors of the production and processing of foods, or even as a consequence of natural processes [6,7]. Recent evidence suggests that diet influences the bio-accessibility of food contaminants, and these contaminants have been associated with adverse metabolic health effects [8,9]. Indeed, several major food components of the MedDiet are sources of some environmental chemicals, such as vegetables, cereals or fish, which can be exacerbated by various food preparation methods [10]. During processes such as baking or frying, chemical and biochemical reactions occur, including Maillard reactions, which have the potential to generate contaminants such as 5-hydroxymethylfurfural (HMF) or acrylamide [11,12]. Furthermore, additional preparation techniques, including drying and smoking, facilitate the formation of these contaminant compounds, such as polycyclic aromatic hydrocarbons [12]. In fact, thermal processing is the most prevalent method employed in food preparation, appearing in over 80% of foods consumed [13].

Concurrently, the consumption of ultra-processed foods is on the rise, which may be associated with adverse health outcomes [14,15]. Indeed, even Mediterranean countries are currently diverging from the traditional dietary recommendations of the region, for example Spain, which has undergone a notable shift in contemporary food consumption patterns [16,17]. Ultra-processed food products can also represent sources of additional dietary contaminants, including certain foods additives or plastic food contact chemicals from their packages [18]. Moreover, the use of some additives is currently under scrutiny due to their potential health effects if misused. For example, nitrogen derivatives such as nitrates or nitrites present the greatest potential for dietary exposure, particularly given their use as additives in processed meat products [19,20].

In light of the rising incidence of deviations from traditional dietary patterns, which could reduce the contaminants exposure favouring local and minimally processed foods [20,21], numerous organizations, including the European Food Safety Authority (EFSA), have made it their mission to reduce the intake and exposure to these contaminants [22].

However, there is a need for further studies based on nutritional epidemiology, particularly longitudinal studies, in order to quantify the effects of dietary strategies maintained over time on clinical outcomes, adherence, and possible adverse effects of other contaminants derived from food processing. Although there are trials that provide substantial evidence for some contaminants, such acrylamide [23], there is insufficient focus on the incorporation of other of these compounds into population studies because of the difficulty of their estimation. However, some important studies such as the NutriNet-Santé cohort [24], or E3N (Étude Épidémiologique auprès de femmes de la mutuelle générale de l'Éducation Nationale) [25], are estimating some of these contaminants through dietary surveys, providing insightful information, and highlighting the need of their evaluation within dietary intervention contexts, with healthy dietary patterns, such as the MedDiet.

The aim of this study is to evaluate the intake and exposure to 11 contaminants present in processed foods in a Spanish population and to examine the impact of a dietary intervention based on a Mediterranean dietary pattern. Utilising a dietary survey approach, this study explores the potential of the Mediterranean diet as a nutritional strategy to mitigate the impact of contaminants and their influence on anthropometric variables.

2. Methods

2.1. Population of the study

This study is contextualized within the framework of the randomized, multicentre clinical trial PREDIMED-Plus, which is focused on the prevention of cardiovascular disease (CVD) [4]. In an overview, the study population comprised men/women aged 55/60 to 75 years, with a body mass index (BMI) between 27 and 40 kg/m^2, and who met the criteria for metabolic syndrome (MS). Individuals with a history of CVD, chronic medical conditions, psychiatric disorders, or allergies to Mediterranean diet ingredients, among other exclusion criteria, were not permitted to participate [4]. Eligible participants were randomly assigned to either an intervention group, which received a traditional hypocaloric MedDiet, physical activity promotion, and behavioural support, or a control group, which received a non-caloric-restricted MedDiet [26]. All participants provided informed consent, and the study was conducted in accordance with the ethical standards set forth in the Declaration of Helsinki. The PREDIMED-Plus study protocol is accessible at http://predimedplus.com and has been registered with the International Standard Randomized Controlled Trial (ISRCTN89898870; http://www.isrctn.com/ISRCTN89898870). For this sub-study, 225 participants were included from one of the 23 centers of the PREDIMED-Plus study, the center at University Clinic Hospital in Malaga between 2013 and 2016. The subjects included in the study had all the needed information for the present analysis available, including baseline data and follow-up data from the first and second years of the study. During this 2-year period, data were collected at the monthly or each two months clinical visits and this included personal data, anthropometric data (e.g., waist circumference, hip circumference, weight, height) and dietary data collected in 3 time points (at baseline, year 1 and year 2).

2.2. Dietary information

Dietary data were collected using a previously validated 143-item food frequency questionnaire (FFQ) [27]. The FFQ was employed to collate data concerning the types and quantities of food and beverages consumed by the subjects. In order to identify the most representative source of contaminant exposure, the FFQ items were classified into 14 food groups (milk and milk products; eggs, meats and meat derivatives; fish, fish products, seafood and crustaceans; vegetables; tubers; fruit; nuts and spices; legumes; cereals; oils and fats; pastry; miscellaneous; beverages without alcohol; alcoholic beverages). Furthermore, adherence to the MedDiet was evaluated using a validated instrument, 17-item MedDiet [26,28]. The MedDiet-17 is a questionnaire designed to assess adherence to a calorie-restricted Mediterranean diet, especially in overweight or obese individuals. This instrument, which contains 17 items, has been validated in the PREDIMED-Plus study. In essence, the scale measures an individual's adherence to a dietary pattern characterised by the consumption of foods typical of the Mediterranean diet and the reduction of less healthy products [28].

2.3. Food contaminants estimation

This study employed the CONT11 database, which collates data on a substantial number of contaminants that have the potential to be present in food. The contaminants in question are 5-Hydroxymethyl-2-Furfural (HMF5), Acrylamide (ACRYL), Furan (FURAN), Furosine (FUROS), Pyrraline (PYRR), Amadori compounds (AMCOMP), Benzopyrene (B(A)P), Total Polycyclic Aromatic Hydrocarbon (TPAHC), Nitrates (NITRA), Nitrites (NITRI) and Nitrosamines (NITRN) [29]. The CONT11 database adheres to the established methodology of food composition databases (FCDB). The data presented in CONT11 were sourced from 35 distinct studies and repositories, covering different geographical realities, as the database includes data from scientific literature and databases of official international organizations, such as the World Health Organization or the European Food Safety Authority [29]. Only the values relating to contaminants in water were relative to the maximum values stipulated by Spanish legislation [30]. CONT11 collected values for a total of 220 foods, 45 of which exhibited different values depending on the processing method employed, including boiling, frying, baking, grilling or roasting [29]. As with other nutrients, contaminants were expressed in milligrams or micrograms per 100 g of food [29]. The calculation of contaminant intake was based on the intake values of each food item and the CONT11 concentration of each contaminant. Individual exposure to such contaminants was determined by dividing the daily intake of the contaminant by the subject's body weight. The data were expressed in units of milligrams or micrograms of contaminant per kilogram of body weight per day. The methodology employed in this study was based on that used in other similar research, which utilized weighted averages of contaminant levels for food items in the FFQ, with concentrations dependent on the cooking method [29,31].

2.4. Statistical analysis

The statistical analysis was conducted in Python, employing the *pandas*, *scipy* and *statsmodels* libraries. The data were grouped according to the categorical variables “Group,” “Year,” and “Adherence to the Mediterranean diet.” The normality of the data in each group was evaluated using the Shapiro-Wilk test. In the event that all groups exhibited a normal distribution, the Student's t-test or ANOVA test was employed. The non-parametric Mann-Whitney *U* test and the Kruskal-Wallis test were employed in cases where at least one group exhibited a non-normal distribution. Additionally, the Friedman test was used to compare variables over time (Year). Statistical significance was set at $p < 0.05$. Other complementary statistical tests, such as the Spearman correlation and Principal Component Analysis (PCA), were also performed. Finally, multiple linear regressions were conducted, with age and sex entered as covariates.

3. Results

3.1. Characteristics of the study population

Table 1 presents a summary of the characteristics of the participants involved in the study, stratified into two groups according to the level of intervention. The results show evidence of a homogeneous distribution with regard to ages, weight, body mass index (BMI) and adherence to the Mediterranean diet at the baseline assessment for both groups. Furthermore, it is notable that over time, there has been a considerable positive change in the anthropometric parameters of the population (weight, BMI, waist and hip circumferences) in comparison to the baseline data, regardless of the level of intervention. The only notable difference between the intervention and control groups was in adherence to the Mediterranean diet, with a higher improvement for the intervention group, which increased consistently and independently of the passage of time.

3.2. Intake and exposure to contaminants

As result of the adoption of the MedDiet, our findings illustrate a notable decline in the intake of the majority of dietary contaminants over time, as it has been clearly observed in Fig. 1. Interestingly, the intervention group exhibited a more pronounced fall in intake of numerous contaminants over time, including PYRR, ANCOMP, FUROS, ACRYL, NITRI, and NITRN, in comparison to the control group. However, NITRA and TPAHC showed an increase. Table 2 presents the data of the exposure levels to various food contaminants, during the first and second years. Although no differences were apparent in the baseline between groups, these differences started to be shown in the first year and being maintained during the second one, especially on PYRR, AMCOMP and FUROS. Considering the total amounts, clear reductions have been observed, showing a possible general reduction in contaminant exposure over time.

The principal sources of the different food contaminants are presented in Fig. 2. It has been observed that some specific categories of food are the primary source of certain contaminants. Vegetables, cereals, dairy products, non-alcoholic beverages and eggs, meats and meat derivatives represent the main sources of exposure to a range of contaminants. For example, vegetables represent the main dietary source of NITRA, while PYR belonged from cereals or HMF5 from beverages without alcohol. However, other contaminants such as ACRYL, B(A)P or TPAH, have a more diversified distribution across multiple food groups.

A PCA analysis was conducted to determine which variables could potentially exert an influence on the exposure to contaminants. Supplementary Material, (File S1) illustrates that, although there is a slight change in the intervention subjects compared to the control group, temporal progression and increased adherence to the MedDiet may exert the most profound influence.

3.3. Relationships between contaminants and characteristics of the study population

Correlation analysis between contaminant intake and the characteristics of the volunteers showed low but significant correlations for the majority of the variables (Fig. 3). A high positive correlation is observed between weight and waist circumference,

Table 1
Characteristics of the study population (n = 225), separated by intervention group and years.

Time	Baseline			1 year			2 year		
Group *(n:125)/(n:100)/(n:225)*	Control	Intervention	Total	Control	Intervention	Total	Control	Intervention	Total
Sex (%) of Woman	54.4	51.0	**52.9**						
Age (years)	64.6 ± 4.7	63.7 ± 5.2	**64.2** ± **5.0**						
Height (cm)	163.1 ± 9.6	162.4 ± 9.4	**162.8** ± **9.5**						
MedDiet-17	7.7 ± 2.5	7.9 ± 2.5	**7.8** ± **2.5** [a]	11.3 ± 2.7*	13.6 ± 2.3*	**12.4 ± 2.8**	11.0 ± 2.8*	13.5 ± 2.4*	**12.1** ± **2.9** [a]
Weight (kg)	88.8 ± 13.1	88.8 ± 12.5	**88.8** ± **12.8** [a]	87.2 ± 13.9	84.1 ± 12.8	**85.8 ± 13.5**	87.5 ± 14.3	84.0 ± 13.1	**86.0 ± 13.9** [a]
BMI (Kg/m²)	33.3 ± 3.4	33.6 ± 3.5	**33.4** ± **3.5** [a]	32.8 ± 3.7	32.0 ± 3.8	**32.4 ± 3.8**	32.8 ± 3.9	31.9 ± 4.0	**32.4** ± **4.0** [a]
Waist circumference (cm)	113.7 ± 9.4	113.8 ± 9.3	**113.8** ± **9.4** [a]	112.3 ± 10.5	108.8 ± 9.6	**110.7 ± 10.2**	113.0 ± 10.6	109.6 ± 10.4	**111.5 ± 10.6** [a]
Hip circumference (cm)	113.7 ± 7.7	114.0 ± 8.0	**113.8** ± **7.8** [a]	112.2 ± 8.5	110.7 ± 8.8	**111.5 ± 8.6**	113.4 ± 9.2	110.9 ± 8.9	**112.3 ± 9.1** [a]

[a] Significant difference between the baseline and two years of intervention. * Significant differences between groups. Statistical significance was set at $p < 0.05$.

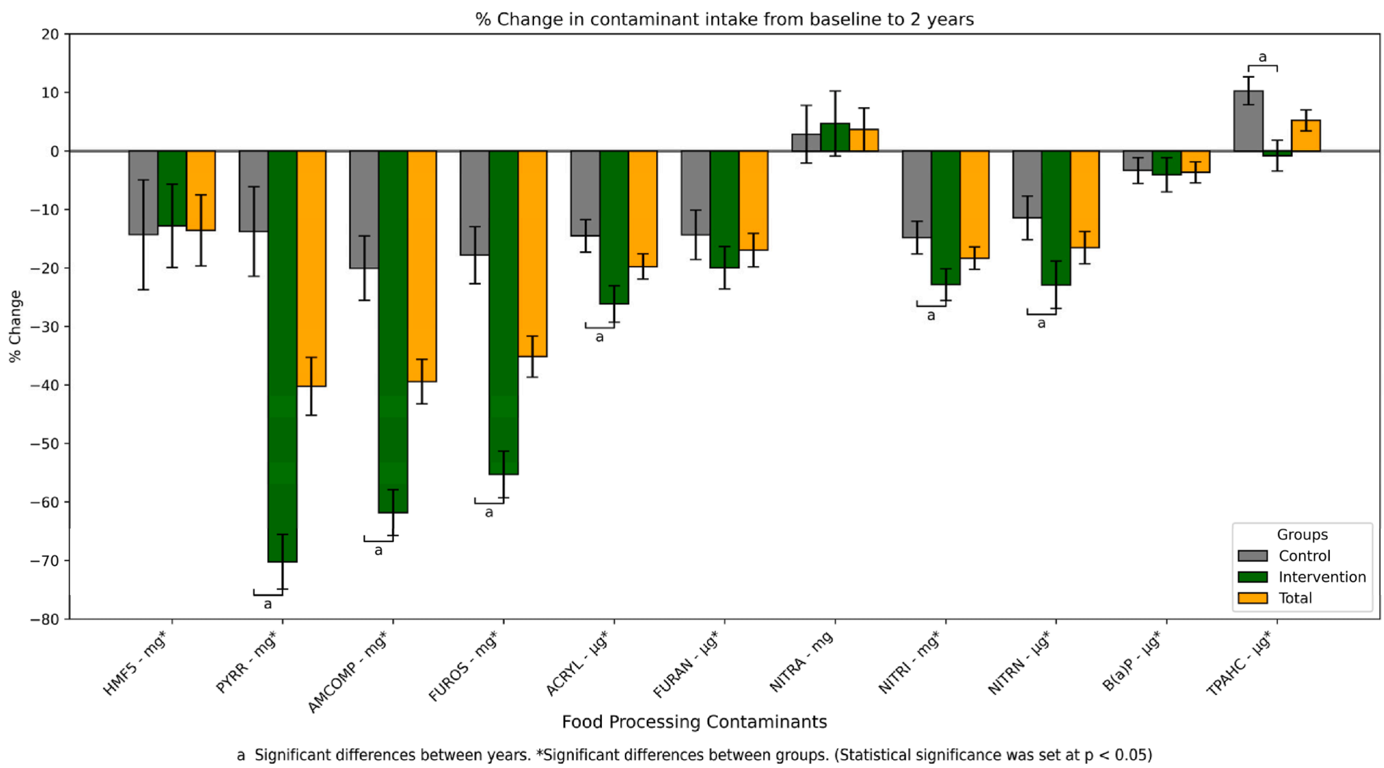

Fig. 1. Percentage change in food contaminant intake over a two-year period following a two-level dietary intervention based on the Mediterranean diet (n: 225). [a]Significant differences between years. *Significant differences between groups. (Statistical significance was set at $p < 0.05$).

whilst both variables suggested an inverse correlation with adherence to the Mediterranean diet. Conversely, adherence to the Mediterranean diet shown negative correlations with the majority of the contaminants, exhibiting particularly pronounced correlations in certain cases, such as AMCOMP, PYRR, FUROS or ACRYL. In contrast, the anthropometric measures exhibited negative correlations with the most contaminants, with the exception of NITRA.

Finally, multiple linear regressions analyses were conducted to examine the potential relations in more detail, revealing that numerous contaminants modulated the anthropometric parameters of the population (Supplementary Material, Table S1), and that diet adherence influenced the intake of the majority of the contaminants (Supplementary Material, Table S2), in a statistically significant way. The findings of the regression analyses indicate a positive association between variables such as AMCOMP and FUROS with BMI, weight and waist circumference. However, adherence to the Mediterranean diet has been observed to exert a significant reductive effect on a number of contaminants with the exception of NITRA, where the trend is inverse.

4. Discussion

4.1. Intake and exposure to contaminants after dietary intervention

Evidence is increasingly showing that the presence of contaminants in food represents a significant risk factor with the potential to have serious consequences for public health. In this context, the identification of mitigation strategies, such as the adoption of healthier and more sustainable dietary patterns, particularly the MedDiet, could prove to be a significant solution [9,32,33]. However, the correct assessment of consumer exposure and intake levels for its correct evaluation in nutritional dietary patterns beyond particular food items is insufficient. Consequently, the implementation of strategies for their reduction has become a crucial aspect of ensuring food safety [34].

On the other hand, previous studies reported that a healthier diet, with high levels of plant-based food, could have a positive influence on the reduction of dietary contaminants [9,34,35]. The MedDiet is considered as one of the healthiest dietary patterns,

Table 2
Exposure values for the different food contaminants according to years and intervention groups of 225 participants.

Time	Baseline			1 year			2 year		
Group (n:125)/(n:100)/(n:225)	Control	Intervention	Total	Control	Intervention	Total	Control	Intervention	Total
HMF5 - mg	1.001 ± 1.242	1.122 ± 1.276	**1.055 ± 1.256**	0.957 ± 1.208	1.066 ± 1.193	**1.005 ± 1.200**	0.889 ± 1.222	1.055 ± 1.306	**0.962 ± 1.260**
PYRR - mg	0.110 ± 0.099	0.120 ± 0.110	**0.114 ± 0.104**[a]	0.093 ± 0.092*	0.039 ± 0.062*	**0.069 ± 0.084**	0.097 ± 0.085*	0.038 ± 0.059*	**0.071 ± 0.080**[a]
AMCOMP - mg	1.213 ± 0.850	1.272 ± 0.916	**1.239 ± 0.878**[a]	0.985 ± 0.757*	0.548 ± 0.454*	**0.791 ± 0.675**	0.986 ± 0.714*	0.530 ± 0.505*	**0.784 ± 0.669**[a]
FUROS - mg	0.396 ± 0.243	0.414 ± 0.264	**0.404 ± 0.252**[a]	0.332 ± 0.222*	0.206 ± 0.138*	**0.276 ± 0.199**	0.331 ± 0.211*	0.201 ± 0.156*	**0.274 ± 0.200**[a]
ACRYL - µg	0.778 ± 0.304	0.784 ± 0.312	**0.781 ± 0.307**[a]	0.695 ± 0.281	0.646 ± 0.262	**0.673 ± 0.273**	0.678 ± 0.274	0.617 ± 0.260	**0.651 ± 0.269**[a]
FURAN - µg	0.197 ± 0.117	0.206 ± 0.119	**0.201 ± 0.118**[a]	0.183 ± 0.114	0.184 ± 0.105	**0.184 ± 0.110**	0.174 ± 0.116	0.177 ± 0.115	**0.175 ± 0.115**[a]
NITRA - mg	2.311 ± 0.981	2.329 ± 1.015	**2.319 ± 0.994**[a]	2.409 ± 1.210	2.569 ± 1.150	**2.481 ± 1.184**	2.421 ± 0.999	2.612 ± 1.241	**2.505 ± 1.114**[a]
NITRI - mg	0.059 ± 0.019	0.057 ± 0.020	**0.058 ± 0.019**[a]	0.051 ± 0.017	0.049 ± 0.019	**0.050 ± 0.018**	0.051 ± 0.017*	0.048 ± 0.020*	**0.050 ± 0.018**[a]
NITRN - µg	0.047 ± 0.021	0.047 ± 0.025	**0.047 ± 0.023**[a]	0.042 ± 0.018	0.042 ± 0.021	**0.042 ± 0.019**	0.043 ± 0.020*	0.040 ± 0.025*	**0.041 ± 0.022**[a]
B(A)P - µg	0.008 ± 0.002	0.007 ± 0.002	**0.008 ± 0.002**[a]	0.007 ± 0.002	0.008 ± 0.002	**0.008 ± 0.002**	0.007 ± 0.002	0.008 ± 0.003	**0.008 ± 0.002**[a]
TPAHC - µg	0.042 ± 0.010	0.044 ± 0.012	**0.043 ± 0.011**[a]	0.049 ± 0.012	0.045 ± 0.012	**0.047 ± 0.012**	0.048 ± 0.011	0.046 ± 0.012	**0.047 ± 0.011**[a]

All contaminant exposure data are: contaminant concentration/kg of body weight (BW) per day.
[a] Significant differences between the baseline and two years of intervention. * Significant differences between groups. Statistical significance was set at $p < 0.05$.

offering a range of benefits for physical and mental health [26,35–37]. MedDiet, characterized by a high consumption of fresh food, has been highlighted as a healthy diet capable of reducing the intake of contaminants, although only a limited number of studies have currently demonstrated it. Particularly important seems to be its possible relationship with the reduction of processed food products [29,32,33,38,39]. Our study has tried to shed light on the matter, as many factors can influence the final concentration of contaminants in a meal, from the origin to the moment to eat. For instance, contamination may be originated from the agricultural use of pesticides, which exhibit high dispersal potential through groundwater flows, atmospheric dispersion or wildlife migration [7]. Furthermore, research has demonstrated that the food trade has been shown to be a significant source of contamination, attributable to factors such as transportation or the practices of packaging [7]. Finally, the specific thermal treatment applied, the inherent characteristics of the ingredients, or the food processing methods employed add important changes in the final concentration and diversity of contaminants [10,40–44]. MedDiet is distinguished by the consumption of primarily fresh and minimally processed foods [45], as well as the use of high-moisture and lower-temperature techniques such as boiling and stewing, something that is pivotal in the preservation of nutrient content and the reduction of the formation of potentially harmful compounds that can result from high-temperature cooking [46]. Taking together, evidence suggests that the adoption of a MedDiet pattern could be associated with lower levels of contaminants intake in relation to an Occidental dietary pattern [45], and in this line, our results may suggest that the adoption of a MedDiet pattern is associated with lower levels of contaminants intake over

Fig. 2. Proportional contribution of the main food groups to the total contaminant intake levels, represented as a percentage (n: 225). Each bar corresponds to a specific contaminant, different colours indicating the relative contribution of various food groups.

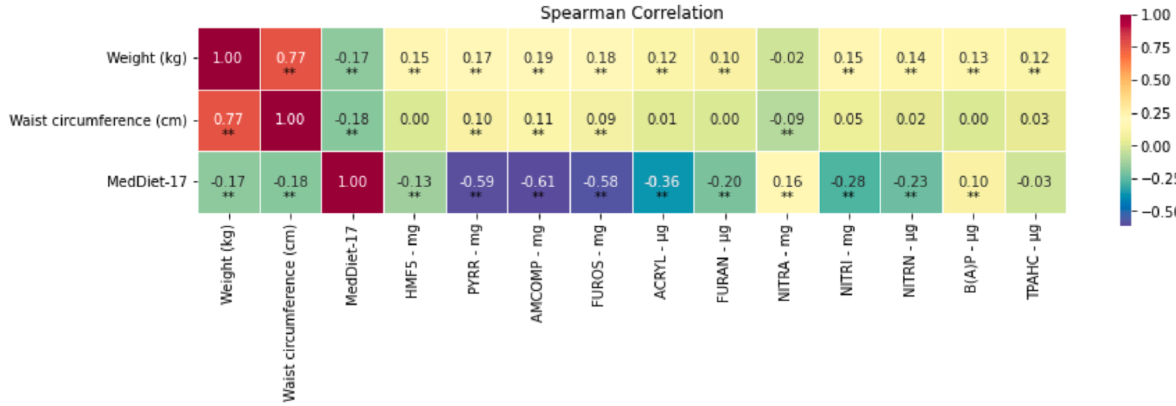

Fig. 3. Spearman Correlation between the intake of contaminants, and different anthropometric measures and Mediterranean diet adherence (n: 225). The colour gradient represents the strength and direction of the correlation, red tones indicate positive correlation and blue tones indicate negative correlations, implying an inverse relationship between the variables. ** Statistical significance was set at $p < 0.05$.

time. In fact, these findings are consistent with those of other researchers who have observed that adherence to a healthier dietary pattern can reduce exposure to contaminants in humans [33–35]. Moreover, our intervention group, the one who accomplished a higher adherence to the Mediterranean diet pattern, showed a higher effect on the reduction of contaminants. This could be attributed to the fact that adherence to a Mediterranean dietary pattern is associated with an increase in the consumption of vegetables and fresh products at expenses of a reduction in the consumption of processed and ultra-processed foods [47–49]. In fact, an earlier study on PREDIMED-plus participants showed, through the use of information from FFQ, a reduction in ultra-processed foods in subjects with a higher adherence to the Mediterranean diet [50].

Ultra-processed foods should be considered as a significant contributor to the increased intake of specific contaminants, particularly acrylamide or nitrosamines [51,52]. An example of this phenomenon was evidenced by a study conducted in the United States population, which directly correlates markers such as acrylamide and glycidamide hemoglobin with the energy contribution of ultra-processed foods [53]. This finding would be aligned with the dietary estimates derived from our study, corroborating the established role of ultra-processed foods as a significant source of acrylamide exposure. On the other hand, globalization has resulted in an increase in imported foods, with a significant rise in processed and ultra-processed foods [54]. This fact highlights the need to adopt a healthy dietary pattern. MedDiet, as well as the planetary diet, which promote the consumption of locally and minimally processed foods could help mitigating intake and exposure to these contaminants [55].

Our study has demonstrated that adherence to the Mediterranean dietary pattern results in an increased intake of plant-based foods. As plant-based foods are the primary source of dietary NITRA levels, this beneficial pattern has been related to an elevated consumption of NITRA [47,48,56]. However, these compounds can have dual effects [57–59]. Depending on the food matrix, NITRA may be related as contaminants or exert beneficial effects due to alterations in their absorption, bioavailability and metabolism [8,60]. Nitrates from processed meats are more likely to be metabolized to nitrosamines [61,62]. Whereas the coexistence of vitamins in combination with plant nitrates alters this way of metabolism [56]. Thus, while the ingestion of fruits and vegetables containing NITRA has been demonstrated to have a beneficial effect on health, often as a result of their combination with other antioxidant components, the negative effects of NITRA are amplified if they come from additives and meat products [58]. Indeed, these compounds can also be converted into NITRN, which are known carcinogens that have a demonstrable negative effect on cardiovascular and metabolic functions [57], but NITRA has also been related to an improvement of the physical performance, a reduction of inflammation and oxidative stress, and with modulation of the gut microbiome and the production of short-chain fatty acids [57]. These contradictory consequences have triggered in no consensus on whether NITRA consumption should lead to alterations in acceptable daily intake recommendations, but showing the necessity to focus on its origin [59].

In the same line, the increase of TPAHC could be related to the use of olive oil, both as a cooking component and as an ingredient [44]. The MedDiet is characterized by the use of olive oil, supporting this increase. Nevertheless, it is important to recognize that the use of olive oil itself introduces variability in terms of bioavailability and absorption [60]. However, depending on its use and whether the oil is consumed raw or after thermal processing, these values could be subject to significant variation. However, the inferred nature of our contaminant calculation approach prevents further exploration of this result.

A focus on other food groups reveals that HMF5 is strongly influenced by non-alcoholic beverages, such as coffee, which is identified as a key actor [63]. Cereals and dairy products, which are recognized as fundamental components of the MedDiet [64], has been identified as major vectors of exposure to multiple contaminants. However, a dietary modification involving an increase in fermented dairy products and a transition from refined grains to whole grains or alternative options has been shown to significantly reduce exposure to this contaminant in humans [65,66]. Alternatively, other food groups have been observed to contribute to increased exposure to contaminants, though their influence does not demonstrate a clear trend or defined pattern [65,66].

The Mediterranean dietary pattern is distinguished by the utilization of healthier and more traditional cooking methods, emphasizing prolonged cooking techniques and the incorporation of spices [2,46,67]. In this context, the use of spices in the Mediterranean dietary pattern may also contribute to reduce exposure to contaminants. For example, rosemary has been shown to be effective in inhibiting the activity of a-glucosidase which may have an impact on the production of precursors of several of the contaminants [41]. On the other hand, the substitution of cooking methods, such as frying, for other methods, including stewing or roasting, has been demonstrated to reduce ACRYL levels [39,68], Furthermore, this alternative method has been demonstrated to result in less thermal damage, which in turn reduces the presence of this contaminants [10,40,43,52,60]. Thus, in order to improve the records of contaminants in our meals, it is imperative to include the cooking methods and the use of spices and dressings.

Another notable outcome of dietary interventions based on the Mediterranean diet is its potential for an improvement in the health status, including the reduction in body weight and other anthropometric parameters [48,69]. Previous research demonstrated that an increase in the adherence to the MedDiet, and consequently the adoption of a healthier lifestyle, result in improvements in anthropometric parameters [26,35–37]. Our results are in line, together with a reduction in intake and exposure to these contaminants, regardless of the weight factor.

Some food contaminants have been related with potential adverse effects on anthropometric parameters, others with a carcinogenic potential [52,70–75]. In accordance with the findings presented, our correlation analysis observed inverse relationships between the decrease in contaminants intake and an improvement in anthropometric variables. Additionally, the findings indicate that an elevated adherence to a Mediterranean diet is significantly associated with a decreased intake of all contaminants, with the exception of NITRA and B(A)P, which exhibit the opposite correlation. With regard to B(A)P, although there is a minor increase, caution should be applied as it is considered to be carcinogenic [76]. This increase could be attributed to the increased use of oil in cooking [44], emphasizing the need of knowing the uses of the different food items. In the case of NITRA, our results suggest that increasing fruit and vegetable intake and making changes to food preparation methods, such as incorporating raw foods or using oil as the primary source of energy, may also have a beneficial impact [9,10,34,41,44,60], besides an increased exposure to antioxidant compounds, such as polyphenols, that are beneficial to health [77,78], supporting the association with healthy anthropometric parameters [19]. Additionally, these findings were subjected to further analysis, finding a clear evidence of the impact of contaminants on anthropometric parameters, and indicating that they can exert a significant influence, particularly in the case of FUROS, PYRR and AMCOMP.

Finally, the capacity of MedDiet as a possible strategy for mitigating food contaminants [9,34] could be reinforced for it capacity to exert an effect on the absorption and bioavailability of these substances [8]. For example, an increase in vegetable products, as is typical of the Mediterranean diet, has been shown to affect the pH levels in the gastrointestinal cycle, and to increase the intake of fiber. These factors may reduce the absorption of acrylamide and other contaminants in the gastrointestinal tract [79].

4.2. Limitations and strengths

Despite the fact that the principal advantage of the study is the use of data from a cohort is that it is part of a much larger population, with hundreds of publications behind [4,37], the present study is subject to certain limitations, with the main focus on the estimation of the contaminants exposure on calculations based on a static database as the CONT11 food database. The CONT11 database relays on an average approximation of the different food items, including cooking methods that are typically used in the preparation of foods. Thus, it is important to note that the lack of specification of the cooking methods and other comprehensive specifications could trigger in variations of the calculated values from the expected results. Thus, in spite of the robust methodology besides the CONT11 food database [29], the lack of an empirical validation of the database-derived exposure estimates, reduces its generalizability. Moreover, the use of a food frequency questionnaire (FFQ), in contrast to the more precise method of 24-h dietary records, could reduce its efficacy. However, it is important to note, that this FFQ has been widely reported validated [4,37], used [31,80], and that the results are within the range of values found in other studies [42,62,63,68,74,76,81–83], supporting its validity. Moreover, similar exposures and intakes of contaminants have been reported in other studies with other populations, supporting the tool. In the future, concrete specifications should be included in order to facilitate more accurate estimation of intake and exposure. However, our interesting results deserve further studies matching empirical tests on biological samples with database results, in order to strengthen this nutritional approach for the analysis of the contaminant exposure and intake in great cohorts.

5. Conclusions

Our findings indicate that a dietary intervention based on the Mediterranean diet can lead to sustainable improvements in adherence to a healthy dietary pattern and is linked to reduced estimated intake and exposure to contaminants generated during food processing. In addition to its recognized health benefits, the Mediterranean diet may therefore be considered a practical nutritional strategy for mitigating the effects of dietary contaminants. In view of the observed associations between particular compounds derived from processing and measures of adiposity, it is recommended that future research and dietary guidance explicitly consider food-processing contaminants. In order to better clarify their contribution to obesity and metabolic disease risk, research should be integrated with dietary assessment and biomarker-based exposure approaches.

CRediT authorship contribution statement

Daniel Hinojosa-Nogueira: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Cristina María Díaz-Perdigones:** Writing – original draft, Methodology, Formal analysis, Data curation. **Alba Subiri-Verdugo:** Methodology, Data curation. **Alba Rodríguez-Muñoz:** Methodology, Data curation. **María José García-López:** Methodology, Data curation. **María Rosa Bernal-López:** Methodology, Funding acquisition, Data curation. **Montse Fitó:** Writing – review & editing, Project administration, Funding acquisition. **Jordi Salas-Salvadó:** Writing – review & editing, Project administration, Funding acquisition. **Miguel Ángel Martínez-González:** Writing – review & editing, Project administration, Funding acquisition. **Francisco J. Tinahones:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Isabel Moreno-Indias:** Writing – review & editing, Supervision, Conceptualization.

Ethics statement

The studies involving human participants were reviewed and approved by CEI Provincial de Málaga-Servicio Andaluz de Salud. The participants of the current project research provided their written informed consent to join the study.

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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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.emcon.2026.100645.

Data availability

Data will be made available on request.

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