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Development and validation of an individual sustainable diet index in the NutriNet-Santé study cohort

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Abstract

In the current context of unsustainable food systems, we aimed to develop and validate an index, the sustainable diet index (SDI), assessing the sustainability of dietary patterns, including multidimensional individual indicators of sustainability. Based on the FAO's definition of sustainable diets, the SDI includes seven indicators categorised into four standardised sub-indexes, respectively, environmental, nutritional, economic and sociocultural. The index (range: 4–20) was obtained by summing the sub-indexes. We computed the SDI for 29 388 participants in the NutriNet-Santé cohort study, estimated its validity and identified potential socio-demographic or lifestyle differences across the SDI quintile. In our sample, the SDI (mean = 12·10/20; 95 % CI 12·07, 12·13) was highly correlated to all the sub-indexes that exerted substantial influence on the participants' ranking. The environmental and economical sub-indexes were the most and less correlated with the SDI (Pearson R^2 0·66 and 0·52, respectively). Dietary patterns of participants with a high SDI (considered as more sustainable) were concordant with the already published sustainable diets. Participants with high SDI scores were more often women (24 %), post-secondary graduates (22 %) and vegetarians or vegans (7 %), without obesity (16 %). Finally, the SDI could be a useful tool to easily assess the sustainability-related changes in dietary patterns, estimate the association with long-term health outcomes and help guide future public health policies.

Key words: **Diet indexes: Sustainable diets: Multidimensional assessment: Dietary patterns**

Recently, extensive studies have focused on the identification of more sustainable dietary patterns(1–6). They were defined in 2010 by the FAO as 'those with low environmental impacts, contribute to food and nutritional security and to healthy lives for present and future generations, are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable, are nutritionally adequate, safe, and healthy, and optimise natural and human resources'(7). Indeed, a large shift toward more sustainable diets is fundamental to manage the current challenges encompassing climate change, biodiversity loss, population growth and the expansion of nutrition-related chronic diseases(8–10).

Historically, a large number of organisations have developed indexes based on several indicators to evaluate food security(11). For example, the FAO, in collaboration with the Voices of the Hungry Project, recently developed the Food Insecurity Experience Scale of eight items referring to the level of access to adequate food by the population(12). However, the consideration of sustainability has often been absent when assessing food security, which is mainly based on quantitative and qualitative insufficient intake. In this context, Gustafson *et al.*(13) proposed a seven-metric systems based on a wide range of indicators to assess the sustainable nutrition security within varying world regions.

At the individual level, previous studies proposed indicators to assess the sustainability of diets(6). Most focused on environmental (e.g. diet-related greenhouse gas emissions or land use) or nutritional (e.g. nutrition quality index or compliance with specific dietary patterns) dimensions and often considered only a small number of indicators. They were not based on a multicriteria approach(5). Moreover, most of the studies have not included the environmental indicators as a component of

Abbreviations: Org-FFQ, organic semi-quantitative FFQ; SDI, sustainable diet index.

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the index but have explored the environmental impact of diets based on dietary quality scores[14]. The systematic review of the assessment of sustainable diets conducted by Jones *et al.*[6] highlighted a notable under-representation of social indicators (such as cultural heritage, equity, rights or governance), although the assessment of the social dimension is of central importance for the understanding of the ability of individuals to shift towards more sustainable diets[6,15]. Furthermore, in a recent review by Perignon *et al.*[2], the authors reported that sustainable indicators were not necessarily compatible with each other. Therefore, there is a need to develop a holistic individual index to assess the sustainability of diets encompassing many components.

The purpose of this study was thus to develop a validated index to assess and compare the sustainability of diets in the NutriNet-Santé French cohort, taking into account multiple indicators based on current scientific knowledge and covering the four factors of diet sustainability as defined by the FAO: environmental, nutritional, economic and sociocultural aspects. The content and construct validities of the index were further assessed. Finally, the individual characteristics of the cohort participants were estimated according to their adherence to the index.

Methods

Study design and population

The NutriNet-Santé study was a web-based prospective cohort launched in 2009 in France, previously described in detail elsewhere[16]. Briefly, the participants were Internet-using adult volunteers from the general population. At inclusion and then periodically, the participants had to complete a set of self-administered questionnaires regarding socio-economic status, anthropometrics, lifestyle, physical activity and dietary intake. Moreover, they were regularly invited to complete specific complementary questionnaires.

This study was conducted in accordance with the Declaration of Helsinki, and all of the procedures were approved by the Institutional Review Board of the French Institute for Health and Medical Research (IRB Inserm 0000388FWA00005831) and the Commission Nationale de l'Informatique et des Libertés (CNIL 908450 and 909216). The study was registered at ClinicalTrials.gov (NCT03335644). All the participants provided informed consent with an electronic signature.

Data collection

Dietary intake assessment. From June to December 2014, the participants were invited to complete an annual organic semi-quantitative FFQ (Org-FFQ), based on a previously validated FFQ[17] supplemented by a section to collect information of organic food consumption. The Org-FFQ included 264 items for which participants had to report their consumption frequency (yearly, monthly, weekly or daily units) and the quantity consumed using standard portion sizes. Daily food intake in g/d was obtained by multiplying the portion size and frequency.

The participants were also asked to indicate the frequency of items consumed in their organic forms (certified and labelled agro-ecological practise based on European Union regulations) according to a five-point ordinal scale. Scores of 0, 0·25, 0·5, 0·75 and 1 were allocated to the corresponding respective modalities: never, rarely, half of time, often and always[18]. This enabled us to calculate the share of organic food (in g) in the whole diet and for each food.

Finally, individual nutrient intake was estimated using the published NutriNet-Santé food composition table[19].

Dietary index. We computed a generic nutritional index, the PANDiet[20]. Briefly, the PANDiet reflects the probability of adequacy to French recommendations for twenty-four nutrients: proteins, total carbohydrates, total fats, PUFA, fibre, vitamins A, B_1, B_2, B_3, B_6, B_9, B_{12}, C, D and E, Ca, Mg, Zn, P, K, Fe, SFA, cholesterol and Na. The PANDiet includes two sub-scores: an adequacy sub-score assessing the probability that nutrient intake satisfied the requirements (above a reference value) and a moderate sub-score assessing the probability that nutrient intake was not excessive (over a reference value). The PANDiet is the average of adequacy and moderate sub-scores.

Environmental impact assessment. The diet-related environmental impacts were assessed using a specifically developed French database of environmental indicators of raw agricultural products collected from DIALECTE[21] and completed with published literature data. Three indicators were included in the database: greenhouse gas emissions (in kg CO_{2eq}), primary energy consumption (in MJ) and land occupation (in m^2). A set of conversions extensively described elsewhere[22] were computed to assign environmental indicators, taking into account shifts from raw agricultural products until consumer use as well as the method of agricultural production (organic *v.* conventional) for each food item. Finally, we computed for each a partial ReCiPe (pReCiPe) score, including the greenhouse gas emissions, primary energy consumption and land occupation relative to the food production. This score reflects the environmental impacts of food production and is computed as following[23]: pReCiPe = 0·0459 × greenhouse gas emissions (in kg CO_{2eq}/kg) + 0·0025 × primary energy consumption (in MJ/kg) + 0·0439 × land occupation (in m^2/kg).

Environmental impacts of individual diets were estimated by multiplying the pReCiPe by the quantity of consumed food (g/d), accounting for the method of agricultural production.

In addition, the share of organic food in the diet was used as a proxy for biodiversity preservation in farm[24,25].

Economic-related data assessment. Concomitant to the Org-FFQ, the participants were also asked to complete an optional questionnaire, focusing on attitudes and motivations (Org-AMQ) regarding food choices inquiring about the places of purchase.

A national database gathering the retail prices of each food item, taking into account the place of purchase and the method of food production (organic *v.* conventional), was formed from the 2012 Kantar database and price collections in autumn 2014 and spring 2015 in short supply chain outlets. More information was provided elsewhere[26].

The individual daily monetary cost of diets was computed by multiplying the food quantity consumed (g/d) by the price (€/g). Finally, we assessed the share of budgets allocated to food by dividing the total diet monetary cost by the income reported by the participants[26]. As in the study of Barosh *et al.*[27], we considered that the affordability of diets could be assessed by the percentage of available household income for food. The more the budget allocated to food, the less affordable the diet was.

Practice and motivation data assessment. An index to assess the diversity of purchase places other than supermarkets was developed according to the answers to the Org-AMQ. For thirty-one food groups, the 'favoured' places of food group purchases were declared for each of the methods of production (organic *v.* conventional). To compute the index, two points were assigned for short supply chains defined as direct food commercialisation between producers and consumers or with only one intermediary (producers' markets, farmers' shops, AMAP (associations supporting small farming), artisans, farms and self-production) and one point for other places: markets, groceries, specialised organic shops or cooperatives. No point was attributed to supermarkets. Then the index (out of two) was obtained by summing the points and dividing by the total answers.

We also computed an index to assess the consumption of ready-made products. In the Org-AMQ, the participants were asked to report their frequency of consumption of canned goods, ready-made meals, and frozen foods through a 5-point ordinal scale ranging from 'never' to 'always.' Scores of 0, 0·25, 0·5, 0·75 and 1 were allocated to the corresponding modalities: never, rarely, half of time, often and always. This enabled us to calculate, for each participant, the amounts of ready-made products consumed.

Covariates. The socio-demographic and lifestyle data used were those collected closest to the Org-FFQ completion date.

Socio-demographic data included sex, age (over 18 years), scholar education (< high school diploma, high school diploma and post-secondary graduate), place and area of residence (rural community, urban units with a population <20 000 inhabitants, between 20 000 and 200 000 inhabitants, and >200 000 inhabitants) and monthly income per household unit (<1200 euros, between 1200 and 1800 euros, between 1800 and 2700 euros and >2700 euros per household unit) obtained using the household income by month and the household composition. Lifestyle variables included smoking status (former, occasional, current or non-smoker), level of physical activity as measured by the International Physical Activity Questionnaires[28,29], vegetarian (a diet that did not include any meat) or vegan diets (a diet that excludes all foods of animal origin) and alcohol consumption status (abstainers, moderate drinkers (<14 g alcohol/d), and heavy drinkers).

Weight and height were assessed by a health operator, medical doctor or from self-measurement guided by standardised procedures. BMI (kg/m^2) was then computed and the participants were classified into four groups (underweight, normal weight, overweight ($25 \leq BMI < 30\,kg/m^2$) and obese ($BMI \geq 30\,kg/m^2$)), according to the international BMI classification of the WHO[30].

Development and computation of the sustainable diet index

Based on the available scientific literature in September 2017, we collected information about indicators recommended in other studies[5,11,13,31–39] to assess the diet sustainability herein. These indicators and their links with sustainable diet are presented in Table 1.

The selected indicators were those that[1] covered at least one of the following four fields: environment, economy, sociocultural and nutrition-health and[2] could be computed at an individual level (at this stage, disease burden and respect for the community right were, for example, excluded).

The computation of the index was as follows: a value of 1–5 was assigned to each of the seven indicators as presented in Table 2, using the population quintile values as the cut-offs. For indicators considered 'valuable' for sustainability, one point was assigned to the participants in the first quintile, two points were assigned to the participants in the second quintile and so on. For indicators presumed to be 'damaging' to sustainability, the allocations were reversed.

The indicators in a same domain are equally weighted, except for the ReCiPe which accounts three times that organic food consumption because the ReCIPe gathers the information of three indicators. Then the sub-indexes were obtained by summing up the points provided by each indicator in the same domain and then standardised for obtaining sub-indexes with analogous scale (ranging between 1 and 5). Indeed, the nutrition, economy, environment and sociocultural domains are considered equally important in the sustainable definition of diet at this time. The sustainable diet index (SDI) was then calculated for each individual as the sum of the four sub-indexes ranging from 4 to 20.

Evaluation of the sustainable diet index's validity

The SDI's content validity was tested to estimate the content representativeness or relevance of the indicators of the index[40,41]. First, the relevance of each indicator was justified regarding the FAO sustainable diet definition as shown in Table 1. Second, the correlation between the individual indicators and the SDI and between the sub-indexes and the SDI were estimated (reflecting the importance of each indicator in the ranking). Finally, to better grasp the influence of each sub-index on the SDI ranking, we estimated the concordance between the overall SDI and a modified index computed by removing a sub-index from the total index. The weighted κ coefficients and Pearson correlation coefficients between the SDI and the modified indexes were computed to estimate whether or not one sub-index led the ranking.

The construct validity indicated whether the index correctly assessed the theoretical concept of the phenomenon of interest, here the sustainability of diets. We used external sustainable guidelines to appropriately investigate the construct validity[40,41]. In recent years, many organisations have designed sustainable diets. The World Wide Fund for Nature (WWF) designed French Livewell 2030 diets[42]. In collaboration with the ECO_2 Initiative, the WWF also proposed a French flexitarian plate for low-carbon, healthy and affordable diets[43]. The Solagro non-governmental organisation designed the Afterres2050 scenario, a prospective scenario for the French food system, leading to the definition of a diet meeting several challenges such as climate change, farmers' incomes or ensuring the food quality for the overall population[44]. Our strategy consisted of a qualitative comparison of the relative differences (to avoid artificial discordance due to methodological disparities in the dietary data assessment method) in food group consumption across different levels of sustainability in the diet according to the SDI (fifth *v.* first quintile) with sustainable plates designed by some organisations compared to the diet observed in a national representative population of French adults (INCA2 survey (second national survey of food consumption) 2006–2007, in a sample of *n* 1918).

Statistical analyses

For the present analyses, we selected the participants who completed the Org-FFQ (*n* 37 685). Under- and over-reporters identified by a ratio of energy intake to energy requirement estimated with Schofield equations[45] below or above the previously defined cut-offs were excluded (*n* 2109) as well as those with missing covariates (*n* 391). Finally, the subjects who did not complete the place of purchase questionnaire were also excluded, leading to a final sample of 29 388 participants (online Supplementary material). The SDI was computed for each participant and they were ranked according to SDI quintiles.

Standard statistics (means with 95 % CI or percentages), Pearson correlation coefficients and weighted κ coefficients were computed for the indicators, sub-indexes, and modified SDI by removing the sub-indexes one by one. *Post hoc* differences in means across quintiles were estimated, accounting for multiple testing using Dunnett's correction. For statistical tests, the type I error was set at 5 %. All of the analyses were conducted using SAS 9.4 software (SAS Institute Inc.).

Results

Selection of indicators for sustainable diet index computation

Many indicators were collected from the literature review[5,11,13,31–39] as presented in Table 1. Their links with the sustainability of diet were presented. Because of non-available data to assess some indicators, we had to remove seven at this stage. Some indicators were pooled in a single indicator, as explained in Table 1. Finally, seven indicators composed our index and were allocated to one of the four pillars of sustainability (Table 2).

Content validity

Table 3 shows the distribution of each indicator across the SDI quintiles.

Greenhouse gas emissions, primary energy consumption, land occupation, difference between energy content needed and consumed, share of the budget for food and ready-made product consumption decreased across the SDI quintiles. Conversely, the PANDiet index, contribution of organic food and place of food purchase increased across the SDI quintiles. The maximum of the relative difference between the quintiles was obtained for organic food consumption (68·60 %) and the ReCiPe (57·10 %), whereas indicators with the lowest relative difference was obtained for the PANDiet (14·8 %). The correlations between each sub-index and the SDI were strong. The environmental sub-index was the most correlated with the SDI (R^2 0·66).

Table 4 indicates that whatever the sub-index removed, the ranking of individuals was disturbed to the same extent for each sub-score. Indeed, Pearson correlation coefficients and weighted κ coefficients (based on the quintile of the SDI and the modified indexes) between the modified SDI and the SDI were close (ranging from 0·62 to 0·73).

Results of the construct validity

Table 5 shows the relative differences in food group consumption between the fifth and first SDI quintiles and between the sustainable diets designed by organisations and the French INCA2 consumption data.

An increase in the SDI was associated with less animal food (meat and processed meat, dairy products and milk, seafood and fish), alcoholic beverages, fruit juices and soups and sweet foods (Table 5). Comparable reductions in meat were observed in some sustainable diets. Disparities were observed in fish, eggs and dairy product consumption. Indeed, fish and egg consumption was drastically decreased in the Afterres2050 plate compared to the French INCA2 consumption, while their consumption increased in the WWF Livewell 2030 plate. The consumption of dairy products was increased only in Livewell 2030 plate.

An increase in SDI was also associated with an increase in the consumption of fruits, vegetables and legumes, but the differences between the fifth and first quintiles were less marked than those observed when comparing the modelled sustainable plates with French INCA2 consumption.

Socio-demographic characteristics of participants across quintiles

Table 6 shows the lifestyle and socio-demographic characteristics across the SDI's quintiles. All of the factors were significantly associated with the SDI. The participants with the most sustainable diets in our study (the fifth quintile) exhibited more favourable socio-economic characteristics and lifestyle such as higher incomes, post-secondary degrees, no smoking or more physical activity. The percentage of women and vegetarians also increased across the SDI's quintiles.

Table 1. Indicators selected from the literature review* by sustainability factors, choices of inclusion or exclusion and potential transformation

Indicators	Links with sustainable diets	Choice	Transformation	Indicators in the sub-index
Nutritional				
Dietary energy balance	Excessive energy consumption is acknowledged to be a risk factor of various health outcomes and represents also food wastage. Low energy consumption induces organism malfunctions	Included	We selected the absolute terms of difference between the needs estimated with the Schofield equation and energy content intake to disadvantage participants with an unbalanced energy balance	Absolute value of difference between energy content needed and intake
Dietary energy density Dietary diversity index Micronutrient deficiencies of vitamins and minerals	Diet diversity with nutrient adequacy is essential to avoid micronutrient deficiencies, and health outcomes associate	Included	We selected a generic nutrient adequacy index	PANDiet[20]
Environmental				
Water footprint	Clean water resource is becoming scarce in zones	Excluded: no data		
N footprint	N balance is essential to avoid eutrophication and harmful algae blooms	Excluded: no data		
Carbon footprint	Anthropogenic greenhouse gas emissions contribute to climate change	Included	We used a generic score, the pReciPe	pReCiPe
Non-renewable energy (without fossil fuels) Use of fossil fuels	Some food systems are strongly dependent of non-renewable energy, which gets exhausted	Included		
Land use	Arable land available are limited; moreover, land use change impacts the biodiversity preservation	Included		
Preservation of biodiversity in farm	Some food production methods may accentuate pressures by diminishing biodiversity	Included	Importance of organic production in the food production system	Contribution of organic food to diet
Seasonality	Preference for seasonal food avoids transport or use of conservation methods	Excluded: data too weak		
Packaging	Reduction in packaging and their substitution by eco-packaging saves resources and waste processing	Excluded: data too weak		
Economic				
Food losses and waste	Environmental and economic costs associated with food waste and losses are huge	Excluded: no data		
Affordability: budget allocated to food	Diet must be available at prices that people can afford to pay and in particular low-income consumers	Included	No	Proportion of income devoted to diet
Fair trade	Fair trade is an alternative to trading partnership which contributes to fair income, safe and clean working condition, and producers empowerment	Excluded: data too weak		
Sociocultural				
Local (within a nearby area)/regional foods (with a strong territorial specificity)	Consumption of local foods may contribute to territorial development	Included	We produced an index to assess the places of food purchases other than supermarket	Places of food purchases
Diversity of food supply chain	Short supply chains may allow producers to recapture the value of their work, and by consequence increases their income They encourage the interactions between producers and consumers to share the responsibility of common goods management and food providing	Included		
Cultural continuity	Honouring cultural continuity and food preferences are essential for food acceptance	Excluded: no data		
Ready-made products	Ready-made consumption minimises the cooking activities which represent an opportunity for social exchange, cultural heritage preservation and avoiding the standardisation of recipes	Included	No	Ready-made products

pReCiPe, partial ReCiPe.
* Adapted from the available scientific literature[5,11,13,31–39] in September 2017.

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Table 2. Description of indicators and computation of sub-indexes and the sustainable diet index (SDI)

	Indicators	Objectives	Points allocating	Weight in the sub-index	Assessment
Nutritional sub-index (/5)	Absolute value of difference between energy need and intake (kJ/d)	Reflects the adequacy between energy intake and energy requirements	1 point: ind >4259 2 points: 4259 ≤ ind < 2849 3 points: 2849 ≤ ind < 1812 4 points: 1812 ≤ ind <883 5 points: ind ≤883	1/2	Nutrition sub-index = the sum of points × weight
	PANDiet index (/100)	Reflects the adequacy between nutrient intake and French recommendations for twenty-four nutrients	1 point: ind ≤60·7 2 points: 60·7 < ind ≤ 64·7 3 points: 64·4 < ind ≤ 68·2 4 points: 68·2 < ind ≤ 72·8 5 points: ind >72·8	1/2	
Environmental sub-index (/5)	Land occupation (m^2/year): area required to produce raw agricultural products Greenhouse gas emissions (kg CO_2/year): quantity of carbon dioxide, methane and nitrous oxide emissions at the farm level weighted by their 100-year global warming potential Primary energy consumption (MJ/year): consumption at the farm level of renewable and non-renewable energy	The three indicators were computed together in the pReCiPe	1 point: ind >0·38 2 points: 0·38 ≤ ind < 0·29 3 points: 0·29 ≤ ind < 0·23 4 points:0·23 ≤ ind < 0·17 5 points: ind ≤0·17	3/4	Environment sub-index = the sum of points × weight
	Contribution of organic food to diet (% weight)	Mitigation of biodiversity loss in farm	1 point: ind ≤3·02 2 points: 3·02 < ind ≤ 15·5 3 points: 15·5 < ind ≤ 30·3 4 points: 30·3 < ind ≤ 54·1 5 points: ind > 54·1	1/4	
Economic sub-index (/5)	Proportion of the income devoted to diet (%)	Assesses the affordability of diet	1 point: ind >16·4 2 points: 16·4 ≤ ind < 11·4 3 points: 11·4 ≤ ind < 8·45 4 points: 8·45 ≤ ind < 5·40 5 points: 5·40 ≤ ind < 1·27	1	Economy sub-index = the sum of points × weight
Sociocultural sub-index (/5)	Place of food purchase (/2)	Index to evaluate the frequency of food purchase places other than supermarket*	1 point: ind <0·28 2 points: 0·28 ≤ ind < 0·45 3 points: 0·45 ≤ ind < 0·60 4 points: 0·60 ≤ ind < 0·79 5 points: ind ≥0·79	1/2	Sociocultural sub-index = the sum of points × weight
	Ready-made products (/3)	Index to assess the consumption of ready-made products†	1 point: ind ≥1·75 2 points: ind = 1·5 3 points: ind = 1·25 4 points: ind = 1·00 5 points: ind ≤1	1/2	
Total (/20)		SDI = nutritional + environmental + economic + sociocultural			

pReCiPe, partial ReCiPe.

* For each food group, the privileged places of purchase were collected according to the mode of production (organic *v.* conventional). To compute the index, we assigned two points if the following food places were cited (markets of producers, farmers' shops, AMAP (associations supporting small farming), artisans, farms and self-production), then we assigned one point if the following food places were cited (markets, groceries, specialised organic shops or cooperatives). Then we summed the points and divided by the number of answers.

† To assess ready-made products, the participants were asked to report their frequency of consumption of canned goods, ready-made meals and frozen foods via a five-point ordinal scale ranging from 'never' to 'always'. Scores of 0, 0·25, 0·5, 0·75 and 1 were allocated to the corresponding modalities: never, rarely, half of the time, often and always. This enabled us to calculate, at the individual level, the share of ready-made products.

Discussion

The present study described a new index, the SDI, to assess the sustainability of diets at the individual level. This index is composed of four equally weighted sub-indexes reflecting the four sustainable fields (environmental, nutritional, economic and sociocultural aspects) as defined by the FAO in 2010[7].

The evaluation of the content validity based on the correlation assessment and the evaluation of the concordance between the overall index and a modified index showed that all of the sub-indexes and their indicators contributed independently to the global SDI, arguing for their inclusion in the index. The environmental sub-index was the most correlated with the SDI. This result may be explained by the different correlation structures between the indicators of each sub-index, which remains an unresolved issue for the index's development[46,47].

Only the absolute difference between energy consumption and needs was poorly correlated with the SDI. Indeed the participants with low energy intake *v.* needs obtained a lower index value for this specific indicator, while recent published studies have documented that a low energetic diet is often associated with a lower environmental impact (greenhouse gas emissions or land use)[2]. Thus, the conflict between these indicators may explain the poor correlation with the SDI. Moreover, the self-reported food consumption methods such as

Table 3. Sustainable diet index (SDI), sub-indexes and indicators across quintiles (Q)* of the SDI, the Pearson correlation coefficient and the NutriNet-Santé Study, 2014 (*N* 29 388)
(Mean values and 95 % confidence intervals)

	Q1 (*n* 5561)		Q2 (*n* 5966)		Q3 (*n* 6023)		Q4 (*n* 5685)		Q5 (*n* 6153)		Total (*n* 29 388)			
	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	Pearson correlation coefficient	95 % CI
Total score	8·18	8·16, 8·18	10·55	10·53, 10·55	12·12	12·10, 12·12	13·60	13·58, 13·60	15·74	15·72, 15·74	12·10	12·07, 12·13		
Environmental sub-score	1·89	1·87, 1·92	2·50	2·47, 2·52	2·98	2·95, 3·00	3·45	3·42, 3·47	4·10	4·08, 4·12	3·00	2·99, 3·01	0·66	0·65, 0·67
ReCIPE	0·42	0·42, 0·42	0·33	0·33, 0·34	0·28	0·28, 0·28	0·24	0·23, 0·24	0·18	0·18, 0·19	0·29	0·29, 0·29	–0·51	–0·52, 0·51
Contribution (in percentage of weight) of organic food to the diet	0·15	0·14, 0·15	0·22	0·21, 0·23	0·28	0·27, 0·28	0·35	0·34, 0·35	0·48	0·47, 0·48	0·295	0·292, 0·298	0·43	0·42, 0·44
Nutritional sub-score	2·21	2·18, 2·23	2·69	2·67, 2·72	3·00	2·98, 3·03	3·28	3·26, 3·31	3·75	3·72, 3·77	3·00	2·99, 3·01	0·53	0·52, 0·53
Difference between energy content needed and intake in absolute term (kJ)	3284	3230, 3335	2816	2766, 2866	2653	2602, 2699	2548	2498, 2598	2155	2105, 2201	2682	1992, 2703	–0·21	–0·22, 0·19
PANDiet (/100)	61·32	61·16, 61·48	64·22	64·06, 64·37	66·41	66·26, 66·56	68·72	68·56, 68·87	72·02	71·87, 72·17	66·62	66·54, 66·70	0·57	0·56, 0·58
Economic sub-score	1·85	1·82, 1·88	2·62	2·59, 2·65	3·09	3·06, 3·12	3·46	3·42, 3·49	3·90	3·87, 3·93	3·00	2·98, 3·02	0·52	0·51, 0·53
Share of budget to food (%)	17·68	17·48, 17·88	13·29	13·10, 13·49	11·24	11·05, 11·44	9·92	9·72, 10·12	8·09	7·90, 8·28	11·96	11·86, 12·06	–0·41	–0·42, 0·40
Sociocultural sub-score	2·23	2·21, 2·26	2·74	2·71, 2·76	3·06	3·03, 3·08	3·41	3·39, 3·44	4·00	3·97, 4·02	3·10	3·09, 3·11	0·57	0·56, 0·57
Place of food purchase	0·37	0·36, 0·38	0·47	0·46, 0·48	0·53	0·52, 0·54	0·60	0·60, 0·61	0·74	0·73, 0·75	0·55	0·55, 0·55	0·44	0·44, 0·45
Ready-made products (/3)	1·45	1·44, 1·46	1·30	1·29, 1·31	1·19	1·18, 1·20	1·09	1·08, 1·10	0·92	0·91, 0·93	1·19	1·19, 1·19	–0·44	–0·45, 0·43

* Quintile of sustainable index.

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Table 4. Global and modified sustainable diet index (SDI) across quintiles (Q)* of the SDI, the NutriNet-Santé Study, 2014 (*n* 29 388) and the sensitivity analyses
(Mean values and 95 % confidence intervals)

	Q1 (*n* 5561) (4·00–9·50)		Q2 (*n* 5966) (9·75–11·25)		Q3 (*n* 6023) (11·50–12·75)		Q4 (*n* 5685) (13·00–14·25)		Q5 (*n* 6153) (14·25–20·00)				
	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	Pearson correlation coefficient†	95 % CI	Weighting coefficient *κ*‡
SDI	1·78	1·77, 1·79	3·16	3·15, 3·17	4·13	4·11, 4·14	4·98	4·97, 4·99	6·15	6·13, 6·15			
SDI without sociocultural sub-index	7·93	7·89, 7·97	10·42	10·38, 10·45	12·09	12·05, 12·13	13·58	13·55, 13·62	15·66	15·63, 15·7	0·91	0·9, 0·91	0·72
SDI without economic sub-index	8·44	8·39, 8·49	10·57	10·53, 10·62	12·05	12, 12·09	13·53	13·48, 13·57	15·79	15·75, 15·83	0·92	0·92, 0·92	0·62
SDI without nutritional sub-index	7·96	7·92, 8	10·48	10·44, 10·51	12·16	12·13, 12·2	13·76	13·72, 13·79	15·99	15·96, 16·03	0·85	0·85, 0·85	0·73
SDI without environmental sub-index	8·38	8·35, 8·42	10·74	10·7, 10·77	12·2	12·16, 12·23	13·54	13·5, 13·58	15·53	15·49, 15·56	0·92	0·91, 0·92	0·69

* Quintile of sustainable diet index.
† Correlation coefficient between the index and the transformed index (without sub-indexes).
‡ Measured according to differences in the distribution of individuals in the quintiles of the SDI and the transformed index tested (without sub-indexes).

Table 5. Relative differences in food intake between extreme quintiles (Q)* of the sustainable diet index (SDI), the NutriNet-Santé Study, 2014 (*n* 29 388) and different sustainability scenarios of transition

	Relative difference							
	Q5–Q1 SDI (%)		Flex† – INCA2‡ (%)		Afterres§ – INCA2‡ (%)		Livewell‖ – INCA2‡ (%)	
Alcoholic beverages	–34·56	↓¶	–51·55	↓	–27·00	↓	–26·36	↓
Fruits and fruit-based foods	26·70	↑**	–7·89		35·73	↑	21·19	↑
Vegetables and vegetable-based foods	21·83	↑	66·55	↑	22·04	↑	81·62	↑
Cereals and cereal-based foods	–12·86	↓	3·88		85·89	↑	60·20	↑
Legumes, nuts and oilseeds	65·00	↑	1602	↑	231	↑	626	↑
Starchy roots and tubers	–49·04	↓	–5·66		–15·95	↓	32·08	↑
Eggs	–16·49	↓	161·44	↑	–28·10	↓	30·72	↑
Meat (beef, pork and lamb without processed meat)	–74·07	↓	–77·87	↓	–45·67	↓	–63·78	↓
Poultry	–56·98	↓	–2·82		–9·09		0·31	
Processed meat	–68·54	↓	–56·27	↓	MD		–50·44	↓
Dairy products and milk (without cheese)	–27·67	↓	–9·31		–51·07	↓	6·80	
Cheese	–58·13	↓	–7·19		–64·07	↓	46·71	↑
Fats and oils	4·76		33·59	↑	–4·58		60·31	↑
Sweets	–27·39	↓	–65·78	↓	–27·76	↓	–54·37	↓
Fish and seafood	–13·21	↓	–3·23		–74·19	↓	48·39	↑
Mixed dishes	–49·85	↓	1·10	↓	MD		–96·32	↓
Snacks, desserts and other foods	–42·80	↓	–80·48	↓	MD		–69·63	↓
Vegetable juices, fruit juices and soups	–9·53	↓	–91·05	↓	MD		–55·23	↓
Difference in energy intake (kJ)	–2527		234		–628		1188	

MD, missing data; WWF, World Wide Fund for Nature.
* Quintile of the sustainable diet index.
† Flex: flexitarian plate from WWF and ECO_2[43].
‡ INCA2: individual and national study of food consumption (2006–2007 in France).
§ Afterres2050: plate developed in the Afterres2050 scenario from Solagro[44].
‖ Livewell 2030: plate from WWF[42].
¶ A 15% decrease or more.
** A 15% increase or more.

FFQ are prone to measurement errors and mostly lead to overestimation[48] which could also explain the low correlation observed, even if our FFQ was previously validated[17].

The last test performed (modified index by removing a sub-index) for evaluating the content validity showed that all of the sub-indexes exerted substantial influence on the participants' scoring and ranking. Indeed, removing one sub-index from the SDI disturbed the participants' ranking with almost the same strength for each sub-index. Interestingly, no sub-index appeared to lead the ranking. The Pearson correlation coefficients and weighted *κ* coefficients between the modified SDI and the SDI were of similar extent in any case.

Table 6. Sociodemographic and lifestyle characteristics across quintiles (Q) of the sustainable diet index and the NutriNet-Santé Study, 2014* (*n* 29 388)

	Q1 (*n* 5561) (4·00–9·50)	Q2 (*n* 5966) (9·75–11·25)	Q3 (*n* 6023) (11·50–12·75)	Q4 (*n* 5685) (13·00–14·25)	Q5 (*n* 6153) (14·25–20·00)	*P*†
Sex (%)						<0·0001
Female	61·54	69·53	75·11	81·07	85·76	
Male	38·46	30·47	24·89	18·93	14·24	
Energy intake (kJ/d)	10050 (9987–10117)	8644 (8581–8707)	8071 (8008–8134)	8071 (8008–8134)	7523 (7460–7581)	<0·0001
Monthly income per household unit (%)						<0·0001
Refused to declare	4·06	5·75	6·28	7·25	6·91	
<1200 euros	26·09	14·47	9·33	6·28	2·65	
1200–1800 euros	37·33	29·62	22·93	17·1	9·48	
1800–2700 euros	22·93	28·95	30·73	30·2	24·23	
>2700 euros	9·58	21·22	30·73	39·17	56·74	
Degrees of scholar education (%)						<0·0001
Primary	30·95	23·85	20·07	18·4	13·78	
Secondary	17·44	15·24	14·28	13·81	12·55	
Post-secondary	51·61	60·91	65·65	67·79	73·67	
Location (%)						<0·0001
Rural community	24·4	23·4	22·03	21·34	21·29	
Urban unit: population <20 000 inhabitants	19·46	18·35	17·98	19·17	18·38	
Urban unit: population between 20 000 and 200 000 inhabitants	16·62	15·54	16·04	13·98	14·42	
Urban unit: population >200 000 inhabitants	39·53	42·71	43·95	45·51	45·91	
Alcohol consumption status (%)						<0·0001
Non-drinker	5·7	5·16	4·96	5	6·21	
Moderate drinker (<14 g/d)	69·0	72·8	73·9	76·8	78·1	
Heavy drinker	25·3	22·0	21·1	18·2	15·7	
Physical activity (%)						<0·0001
Missing data	12·64	10·79	9·98	10·48	10·14	
High (>60 min/d)	33·99	34·88	33·82	33·54	31·89	
Medium (30–60 min/d)	30·68	33·57	37·11	38·28	41·69	
Low (<30 min/d)	22·69	20·75	19·09	17·7	16·28	
Tobacco status (%)						0·0689
Former smoker	41·22	39·84	39·98	40·63	40·83	
Occasional smoker	2·9	3·34	3·67	3·29	3·41	
Current smoker	10·65	8·1	7·37	6·44	4·96	
Never smoker	45·24	48·73	48·98	49·64	50·8	
Diet (%)						<0·0001
Omnivorous	99·69	98·81	97·28	95·32	92·1	
Vegan	0·04	0·28	0·95	1·69	2·58	
Vegetarian	0·27	0·91	1·78	2·99	5·31	
BMI (%)						<0·0001
BMI <18·50 kg/m^2	2·81	3·25	4·12	5·22	7·83	
18·50–24·99 kg/m^2	46·3	56·79	61·18	66·37	73·67	
25·00–29·99 kg/m^2	31·95	27·84	25·73	21·79	15·15	
BMI ≥30·00 kg/m^2	18·94	12·12	8·97	6·61	3·35	
Age (%)						
Age <25 years	2·9	2·35	1·76	1·55	0·99	<0·0001
25 ≤ Age <35 years	11·47	10·95	11·59	11·19	9·22	
35 ≤ Age <50 years	27·3	24	22·85	20·93	20·71	
50 ≤ Age <65 years	35·08	36·84	37·42	40·25	42·65	
Age ≥65 years	23·25	25·86	26·38	26·09	26·44	

* Quintile of sustainable index.
† *P* referred to χ^2 test.

This result indicates a relatively good balance between the sub-indexes.

The assessment of the construct validity was relatively more subjective since the gold standard or references were lacking. Indeed, the new French food-based guidelines integrating sustainable consideration should be soon published. Thus, to cope with this issue and to provide elements for external validity, our strategy consisted of comparing the relative differences in food group consumption across different levels of sustainable diets according to the SDI (the first and fifth quintiles) with sustainable transition plates designed by some organisations promoting sustainable development and compared to the current average French diet. These comparisons showed overall consistent results: the changes in terms of food group consumption needed to reach a more sustainable diet, corresponding to a high SDI as herein, or calculations made by organisations were comparable for most food groups, and in particular for those whose production may lead to particularly low or high greenhouse gas emissions or environmental impact such as vegetables and fruits or animal foods, respectively. Also,

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results are consistent with the food classification of van Dooren *et al.*[49] in three groups from red to green according to the sustainable nutrient-rich food (SNRF) index and climate impact of food products. Indeed food exhibiting increased consumption in SDI_{Q5} compared to SDI_{Q1} in our study are those classified in the green class (low greenhouse gas emissions relate to food production and high SNRF), while those with a decrease are in the red class (high greenhouse gas emissions relate to food production and low SNRF). Moreover, meats from ruminants are related to more greenhouse gas emissions, energy and land consumption compared to poultry, pork and eggs[2,4,50] that is why the relative differences in these food group consumption between SDI_{Q1} and SDI_{Q5} are lower than for red meat.

Finally, it is noteworthy that for some food groups, such as fish, egg and dairy products, no consensus has emerged certainly due to the differences in methodological and arbitrary choices concerning the objective function and constraints of linear programming with conflicting views on nutrition (adequate nutrient intake), environment (fish stock collapse or livestock environmental impacts) and contaminant exposition (in particular from fatty fish). Thus, it will be necessary in the future to collect more relevant data relating to the impact of production and consumption on the environment, nutrition, toxicology and the co-production links consideration (for instance, between beef meats and milk).

Our results showed that all socio-demographic or lifestyle factors were significantly associated with the SDI. The participants with the most sustainable diets (the fifth quintile) were more likely to be socially favoured and exhibited healthier lifestyles. Thus, one hypothesis may be that for a part of this population healthy and eco-friendly diets are too expensive in relation to their income and some may encounter difficulties to have a geographical access of sustainable food. That raised questions about the accessibility and/or affordability of sustainable diets for the general population in France, highlighting the need to develop public policies to promote these more sustainable behaviours.

Some limitations in this investigation should be noted. First, as for other indexes developed using an *a priori* method, the development presented several methodological limits[47]. For instance, the choice of 1–5 rating has effect in the index development. We chose to make five categories for each indicator to sufficiently discriminate the participants without having too many categories. Moreover, equal weights to the four sub-indexes were allocated to reflect the absence of hierarchy in the FAO definition. However, as some sub-indexes are composed of only one indicator while others are composed of several, the indicators constituting the sub-indexes in the current version do not have the same weight. This issue could be raised in the future and more data may allow rebalancing the weight of each indicator. For further development of the SDI, it could be useful to include new indicators such as water footprint, fair trade or crop treatment frequency index to account for toxicology and improve the accuracy of some indicator assessment, in particular consumption of ready-made products. Hence, the classification of some indicators within the sub-indexes may be questionable. For instance, the purchase place indicator was included in the sociocultural sub-index, while some implications of short supply chain are related to economic scope (e.g. farmer income). In fact, we tried to include indicators in the more representative sub-index. However, our study is the first, to the best of our knowledge, to develop a holistic approach to compute an index at the individual level, compared to previous studies that assessed sustainability only partially[34]. In the future, it will be important to supplement the SDI with other indicators to improve the index's quality and to better account for potential conflicts between sustainability components. Indeed, as highlighted by Gustafson *et al.*[13], advising an increase in fruit consumption can, in some contexts, intensify the depletion of water or deteriorate the work conditions of vulnerable people labouring in fields. Also, our aim was to assess the sustainability of the diet at an individual level, which implies some decisions. For example, we assessed the affordability using a low-income contribution for food supply[27]. However, at the societal level, this low-income contribution may constitute a threat to the economic viability of sustainable production systems unless the actual cost is paid by the communities using taxes, for instance. Nonetheless, the use of the indicator 'percentage of income contribution for food' seemed closer to the notion of affordability compared to food prices that do not account for income levels. The construct validity assessment was based on some recent works by others but not on a gold standard objectively reflecting the concept of sustainability. Indeed, this scientific domain is rather recent and based on assumptions that have not yet properly been validated and therefore require reinforcement. Finally, the SDI construction was conducted in a French context, based on data from a large but specific cohort that implies caution when extrapolating the findings to other populations. Indeed, the participants were self-selected and exhibited particular characteristics including socio-demographic and dietary patterns and in particular organic food consumption[51–54]. This might have reduced the range of the SDI, with some missing segments of the population. Moreover, the SDI was built with some French-specific indicators, as the PANDiet which is based on French nutrient intake guidelines. Light modifications to some indicator assessments (as PANDiet or the food purchase places) could make the SDI appropriate to assess the sustainability of diet in other Western region. However, a lot of available data are needed, and hence it remains an important challenge. Moreover, further validation would be needed to ensure the relevance of SDI from other cohorts.

Finally, our research exhibited important strengths such as the large population sample, a wide spectrum of behaviours and robust and validated data quality.

In conclusion, the new SDI is based on a multicriteria approach and could be a useful tool to easily assess the sustainability of diets, to follow sustainability-related changes in dietary patterns and to study the link with long-term health to help in guiding future public health policies.

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None of the authors has any conflicts of interest to declare.

Supplementary material

For supplementary material/s referred to in this article, please visit https://doi.org/10.1017/S0007114519000369

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