DOCTORAL (Ph.D.) DISSERTATION

ORSOLYA TOMPA
BUDAPEST
2022

Hungarian University of Agriculture and Life Sciences

Sustainable Diet Optimization and Analysis Applied on the Hungarian Dietary Patterns

[Fenntartható táplálkozás elemzése és optimalizálása magyar táplálkozási mintázatok alapján]

DOI: 10.54598/003260

Orsolya Tompa

Budapest, Hungary

2022

Hungarian University of Agriculture and Life Sciences

Name of Doctoral School: Food Science Doctoral School

PhD School/ Program

Field: Food Science

Head: **Livia Simon Sarkadi, DSc**
Department of Nutrition
Institute of Food Science and Technology
Hungarian University of Agriculture and Life Sciences

Supervisor: **Zoltán Lakner, DSc**
Department of Agricultural Business and Economics
Institute of Agricultural and Food Economics
Hungarian University of Agriculture and Life Sciences

The applicant met the requirement of the Ph.D. regulations of the Hungarian University of Agriculture and Life Sciences and the thesis is accepted for the defense process.

....

Approval of Head of Doctoral School Approval of Supervisor

Table of content

List of Abbreviations 5
1. FOREWORD 1
2. INTRODUCTION 2
  2.1. A brief introduction: dietary water footprint in the scope of sustainable nutrition 2
  2.2. Research questions 5
  2.3. Research aims 6
3. LITERATURE REVIEW 7
  3.1. Sustainable nutrition 7
  3.2. Dimensions, indicators, and metrics of the sustainable food system 10
  3.3. Dimensions, indicators, and metrics of sustainable nutrition 10
    3.3.1. Cultural acceptability as sociocultural metric 12
    3.3.2. Environmental impact as an ecological metric 13
      3.3.2.1. Water footprint 14
      3.3.2.2. Calculation of dietary water footprint 16
    3.3.3. Dietary quality as a health metric 17
      Dietary data and dietary shift 18
  3.4. Compilation of sustainable nutrition database 19
  3.5. Scores as assessment tools for sustainable nutrition 20
  3.6. Statistical analyses on sustainable nutrition 21
  3.7. Dietary scenarios in the field of sustainable nutrition 22
  3.8. Diet optimization in the field of sustainable nutrition 23
    3.8.1. Comparison of dietary scenario analysis and diet optimization: an inverse logic 25
  3.9. Results of previous studies 26
    3.9.1. Association of healthiness and environmental impact of nutrition 26
    3.9.2. Health and environmental – especially water footprint - benefits of sustainable focused-dietary changes 28
    3.9.3. The possible dietary shift towards a more sustainable nutrition 30
    3.9.4. Main contributors to dietary water footprint to total diet among food groups 30
4. METHODS 33
  4.1. Summary and logical relationship of the included studies 33
  4.2. Dietary and water footprint data that provided the base for the sustainable nutrition analyses focused on Hungary 35
    4.2.1. Hungarian Dietary and Nutritional Status Survey 2014 35
    4.2.2. Recommended Dietary intake Values 35
    4.2.3. Agricultural Organization of the United Nations (FAO): Food Balance Sheet 36
    4.2.4. Central Statistical Office of Hungary: food consumption data 36
    4.2.5. Nutrient composition data 36
    4.2.6. Environmental impact data 36
  4.3. Scope and methods of the included studies 37
    4.3.1. Association of food-related water footprint and nutrient composition of the most commonly consumed foods and food categories statistical analyses (S_1) 37
      4.3.1.1. Dietary data, nutrient composition, and water footprint and their compilation 37
      4.3.1.2. Correlation analyses between nutrient density and green and blue water footprint of food items and categories 38

4.3.1.3. Classification of nutrients based on their population intake levels and association with green and blue water footprint 38
4.3.2. Association of dietary water footprint and dietary quality of individual diets – integrative and statistical analyses (S_2) 39
4.3.2.1. Characteristics of the sample 39
4.3.2.2. Dietary and water footprint data and their compilation 40
4.3.2.3. Body composition measurement 40
4.3.2.4. Dietary quality scores 40
4.3.2.5. Correlation analyses and sustainable dietary factor identification 42
4.3.3. Water footprint and dietary quality consequences of alternative diets – dietary scenarios analysis (S_3) 43
4.3.3.1. Dietary and water footprint data and their compilation 43
4.3.3.2. Dietary scenarios 45
4.3.3.3. Development and application of dietary quality scores 48
4.3.3.4. Analyses: an integrative approach 53
4.3.4. The design of the diet optimization model targeting water footprint reduction, while fulfilling nutritional adequacy and respecting cultural acceptability (S_4) 53
4.3.4.1. Dietary and environmental data and their compilation 53
4.3.4.2. Diet optimization model design 55
4.3.4.3. Parameters of the Model 55
4.3.4.4. Phases of Optimization and Models 56
4.3.4.5. Analyses of results 57
5. RESULTS AND DISCUSSION 59
5.1. Association of food-related water footprint and nutrient composition of food items – statistical analyses (S_1) 59
5.1.1. Correlation analyses between blue and green water footprint and energy and nutrient density 59
5.1.2. Nutrient classification is based on their association with blue and green water footprint and population intake 61
5.2. Integrative analyses of dietary records based on dietary water footprint and dietary quality – a practical approach (S_2) 63
5.2.1. Correlation analysis between the total dietary water footprint, dietary quality indicators, and fitness score 63
5.2.2. Classification of nutrients based on their association with total dietary water footprint and advantageous or dis-advantageous health-related aspect 65
5.3. Green and blue water footprint and dietary quality impact analyses of baseline and alternative dietary scenarios (S_3) 66
5.3.1. Comparison of dietary scenarios in the dietary water footprint and dietary quality integrative approach 66
5.3.2. The synergy between dietary quality and environmental impact 70
5.3.3. Differences between the sexes 73
5.4. Sustainable diet optimization (S_4) 74
5.4.1. Dietary water footprint changes in healthy a culturally acceptable-focused diets. 74
5.4.2. Dietary water footprint contribution of food groups and sub-groups to total dietary water footprint 77
5.4.3. The dietary shift towards water dietary footprint reduced, nutritionally adequate, and cultural acceptability-focused diets 81
5.4.4. Problematic nutrients in the water footprint reduced, nutritionally adequate and cultural acceptability-focused diets 86
5.4.5. New Scientific Results 88

6. CONCLUSIONS AND RECOMMENDATIONS 90
  6.1. Observed dietary water footprint and major contributors among foods on the population-level 90
  6.2. Possible reduction of dietary water footprint by dietary changes on the population-level 92
  6.3. Towards the healthier, water footprint friendly, and culturally acceptable diets 93
  6.4. Differences based on sex as an aspect 97
  6.5. Methodological considerations 97
    6.5.1. Dietary scenarios analysis versus diet optimization 97
    6.5.2. Aspects for in-depth analysis of sustainable nutrition 98
7. LIMITATIONS 101
8. SUMMARY 103
9. ÖSSZEFOGLALÁS 107
10. APPENDICIES 1
  10.1. References 1
  10.2 . List of publications on the field of science 11
  10.3 . Supplementary Materials (numbered) 13
  10.4 . Acknowledgements 27

List of Abbreviations

BCFN – Barilla Center for Food & Nutrition

BDA – The Association of UK Dietitians

BWF – Blue Water Footprint

CSO – Central Statistical Office

DQSs – Dietary Quality Scores

EC – European Commission

EFSA – European Food Safety Authority

EU – European Union

FAO – Food and Agriculture Organization of the United Nations

FBDGs – Food-Based Dietary Guidelines

FBS – Food Balance Sheet

FNDSS - Food and Nutrient Database for Dietary Studies

GBD – Global Burden of Disease

GDPR - General Data Protection Regulation

GHGE – Greenhouse Gas Emission

GWF – Green Water Footprint

HDNSS – Hungarian Dietary and Nutritional Status Survey

IDQV – Integrated Dietary Quality Value

LCA – Life Cycle Assessment
LCHF – Low-Carbohydrate and High-Fat diet
LP – Linear Programming
MAI – Mediterranean Adequacy Index
MAR – Mean Adequacy Ratio
MER – Mean Excess Ratio
MRVs – Maximum Recommended Values
NCDs – Non-Communicable Disease
OF – Objective Function
QP – Quadratic Programming
RDIs – Recommended Intake Values
SDG – Sustainable Development Goals
SFA – Saturated Fatty Acids
SNRF – Sustainable Nutrient-Rich Foods
SUSFANS - Food system for health, environment, and enterprise in the European Union
TFA – Trans Fatty Acids
UN – United Nations
USDA – United States Department of Agriculture
WEFE – Water-Energy-Food-Ecosystem
WFN – Water Footprint Network
WFP – Water Footprint
WHO - World Health Organization

1. FOREWORD

“In studying life, you keep diving from higher levels to lower ones until somewhere along the way life fades out, leaving you empty-handed. Molecules and electrons have no life.” (Albert Szent-Györgyi, Internat.Sci.Techn., June 1966)

I find the philosophy and principle of sustainable nutrition a beautiful idea. The traditional approach of nutrition science targets the human organism and its health sometimes breaking down the findings into molecules and interpreting their source, metabolism, and effect of them. Understanding the functions of the parts is the importance of essential, however, to leave out the complex picture may be a mistake. The holistic approach is well-known in the medical sciences and nutrition science as such is no exception of it. Sustainable nutrition, by definition, goes further than that, instead of focusing on the human body, it puts humanity back where it inevitably belongs to their economical, societal, and environmental backgrounds and interprets nutrition as their interaction of them. As follows from it, the dimensions of sustainable nutrition became enormously complex, even more than before. Nutritional science is one of the fields of sciences that is a great difficulty to research since there are numerous factors hard to control in studies: we want to measure the effect of one nutrient while there is a whole other means of diet, physical activity, and individual metabolism and preference to consider. The concept of sustainable nutrition considers an even more complex source of factors; thus, the methodology is being more complex, accordingly. I regard this dissertation as finding the way to interpret and research this complex concept, however, at the time of finishing it, I think the shift towards more sustainable diets is just as simple as the plain truth; the respect for our existence, health, society and at last, but not least our environment could show the way to go towards the more sustainable future.

2. INTRODUCTION

2.1. A brief introduction: dietary water footprint in the scope of sustainable nutrition

One of the most challenging problems for humanity is to ensure a sustainable future. There are different global-scale processes that point toward a possible danger in our future: depletion of natural resources, growing global population, and climate change. From this follows that the recent food system will not be able to nourish the global population and a shift towards a more sustainable food system and nutrition would be essential (Food and Agriculture Organization of the United Nations [FAO] and World Health Organization [WHO], 2019; Fischer & Garnett, 2016). Accordingly, United Nations (UN) defined the Sustainable Development Goals (SDGs), among which there are several addresses the sustainable food system and nutrition, hence, numerous SDGs are related to the food consumption, thus can be affected by the change of it: 1st (no poverty), 2nd (zero hunger), 3rd(good health), 4th (quality education), 5th (gender equality), 12th (responsible production and consumption), 13th (climate Action) (FAO and WHO, 2019). Besides, the European Union (EU) policymakers have also set a target to ensure Europe's food and nutrition security through the SUSFANS (Food system for health, environment, and enterprise in the EU) project, which connects food production and consumption based on the "farm to fork" principle (Rutten et al., 2018). One of the approaches to release this global burden is the concept of sustainable nutrition that, by definition, includes a holistic set of elements besides human health: "Sustainable Healthy Diets are dietary patterns that promote all dimensions of individuals' health and wellbeing; have low environmental pressure and impact; are accessible, affordable, safe and equitable; and are culturally acceptable. " (FAO and WHO, 2019). Consequently, sustainability has been included in several food-based dietary guidelines (FBDGs) and its inclusion has become a necessity, though not always realized (Fernandez et al., 2021; Fischer & Garnett, 2016; Okostányér®, 2016).

According to the definition of sustainable nutrition, dietary or food-related environmental impact, health, socio-cultural and economic aspects have been put into the focus of research in this field (Gazan, Brouzes et al., 2018; Hallström, Carlsson-Kanyama, & Börjesson, 2015; Harris et al., 2020; Jones et al., 2016; Perignon et al., 2016a; van Dooren, 2018; Vettori, Bronzi, Lorini, Cavallo, & Bonaccorsi, 2021). The reduction of the environmental impact of human activities is one of the preconditions to achieving the SDGs, several acts and action plans were developed to protect the environment and natural resources and to keep human activity within the local and planetary boundaries (Vanham et al., 2019). Pressures on the environment created by mankind can be measured by the footprint family and other metrics that help to resolve challenges towards a more sustainable future (Gustafson et al., 2016; Vanham et al., 2019). Sustainable nutrition research predominantly focused on food production-related greenhouse gas emissions (GHGE) but land use, water use, and chemical emission are also often considered indicators (Gazan, Barré et al., 2018; Gazan, Brouzes et al., 2018; Hallström et al., 2015; Hallström, Davis, Woodhouse, & Sonesson, 2018; Jones et al., 2016). As in the case of any production, the food production can be also measured by the burden (i.e. pressure) it takes on the environment, thus the environmental impact of food production and consumption is of critical importance. Food production is responsible for 20-33% of anthropogenic GHGE and 70% of freshwater use, furthermore, the major cause of water pollution and biodiversity loss (FAO and WHO, 2019). In its latest, country-specific recommendations, the European Commission (EC) urges Hungary to act to create more sustainable water—management since, the country is highly exposed to the climate change impact that can lead to floods and drought (European Commission [EC], 2022a). On the other hand, dietary risk factors are the second largest (after tobacco use) contributors to the development of Non-communicable diseases (NCDs), which are the leading cause of death in the developed countries (Institute for Health Metrics and Evaluation [IHM], 2019), thus a shift towards a healthier diet would also be critically important regarding the issue of health. In the scope of sustainable nutrition, the proxy indicator for health dimensions is the nutritional or dietary quality, measured by nutri- or dietary quality scores (DQSs) that are designed to evaluate the risk and protection contributed by foods or diets to the NCDs (Hallström et al., 2018). Both the aspect of health and environmental factors points to the direction of urgent dietary shift; however, it is not as simple due to the sometimes disregarded but maybe the most important factor of sustainable nutrition: the socio-cultural aspects. The traditional, meals, foods and diets, and individual preferences are important factors to consider, since there is no definition for cultural acceptability, sustainable nutrition aims to adhere to the observed diet in the population as much as possible, while nutritionally adequate and environmental impact reduced. The economic or affordability aspects are usually expressed as food prices (Gazan, Brouzes et al., 2018; van Dooren, 2018).

The methodological approaches toward sustainable nutrition can be distinguished into three main categories in general: (1) descriptive and correlative analyses between the metrics of sustainable nutrition, (2) dietary-scenarios analysis: the comparison of baseline and alternative dietary scenarios and their impact, and (3) sustainable diet optimization. Descriptive and correlative analyses aim to identify association and integrative dietary (nutrients, food, and diets) indicators of sustainable nutrition (Hallström et al., 2018). In the case of dietary scenarios analyses, based on the observed baseline scenarios, different alternative scenarios are created, and their environmental (e.g. dietary GHGE) and health (e.g. dietary quality) impact and their associations are evaluated (Hallström et al., 2015; Harris et al., 2020; Jones et al., 2016). On the other hand, in the case of diet optimization, the model is created by the pre-definition of desired characteristics that are the metrics of sustainable nutrition; price, environmental impact, and nutrient composition, while the dietary shift towards it is an outcome (Gazan, Brouzes et al., 2018; van Dooren, 2018).

This dissertation focuses on food-related and dietary water footprint as environmental impact indicators, besides nutritional or dietary quality and cultural acceptability adapted to the Hungary population-level. Previous international studies focusing on dietary water footprint estimated the average observed dietary water footprint (~ 3227 l/capita/day on the European level) and the possible total water footprint reduction in case of shifting to healthier (~ 6%), reduced animal-based food (~18%) or no animal-based food diets (~ 25%) on the global level, however, the results are inconsistent and only multi-country scale research included Hungary, that not did specifically target water footprint or detailed analysis on the country level (Chaudhary & Krishna, 2019; Harris et al., 2020; Jalava, Kummu, Porkka, Siebert, & Varis, 2014). Consequently, previous studies have mainly focused on the change of animal- and plant-based food proportions in the population diets and have regarded energy content and the source of protein as especially important at the nutrient level (Chaudhary & Krishna, 2019; Harris et al., 2020; Jalava et al., 2014; Lares-Michel et al., 2021; Steenson & Buttriss, 2021). To this date, there is only one Hungarian research aimed to quantify and analyse the environmental (carbon) footprint of the Hungarian food consumption, however, without modeling the possible dietary shift and its health-related, socio-cultural or environmental impact consequences (Vetőné Mózner, 2014). Furthermore, the importance to focus on the water footprint of production in Hungary was already pointed out and analysed in the case of other elements of the food chain (Nagypál, Mikó, Czupy, & Hodúr, 2019; Nagypál, Mikó, & Hodúr, 2020).

Accordingly, this research aims to apply the main state-of-the-art methods of sustainable nutrition to analyse and optimize the dietary water footprint, dietary quality, and cultural acceptability adapted to the Hungarian population. Besides, its purpose is to provide insights for nutritional counseling practitioners about the aspect of dietary water footprint to include in their practice. At least but not least, the goal of this dissertation is to provide supporting scientific evidence for the further improvement of the national FBDG for the inclusion of water footprint, as an environmental impact category aspect (Figure 1.)

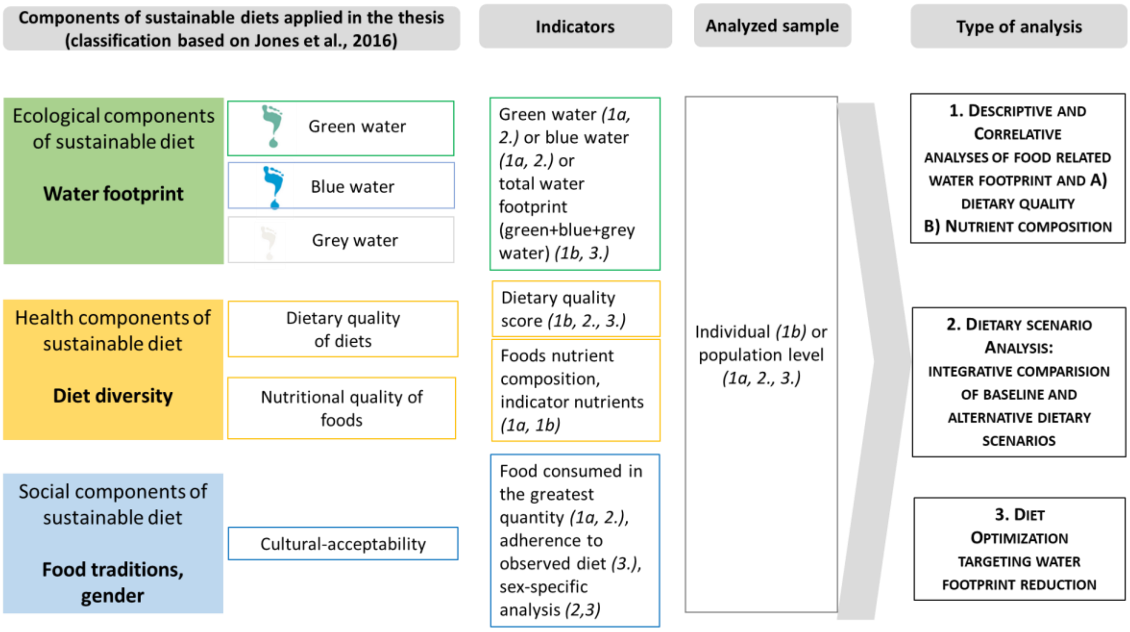


Figure 1: Schematic summary of the basic concept of the dissertation

2.2. Research questions

RQ$_{1}$: How much dietary water footprint reduction is possible on the population-level?

RQ$_{1a}$: How much dietary water footprint reduction is possible in diets optimized to be nutritionally adequate and cultural-acceptability-focused?

RQ$_{1b}$: How much dietary water footprint reduction is possible in alternative dietary scenarios compared to the baseline scenario?

RQ$_{2}$: What are the main contributors among food groups and sub-groups to the dietary water footprint on the population-level?

RQ$_{3}$: What are the health and dietary water footprint impact and their association with baseline and alternative dietary scenarios on the population-level?

RQ$_{4}$: What are the characteristics of water-footprint-reduced and healthier diets at the population-level?

RQ$_{4a}$: What is the most beneficial alternative dietary scenario in the integrative aspect of dietary quality and water footprint?

RQ$_{4b}$: What is the dietary shift from the observed diet to the optimized diet designed to be water footprint-reduced, nutritionally adequate, and cultural-acceptability-focused?

RQ$_{5}$: What are the associations of food-related water footprint and nutrient composition of the most consumed food items and categories on the population-level?

RQ_6: What is the association between dietary water footprint and dietary quality on the level of nutrients?

RQ_{6a}: What are the indicator nutrients for dietary water footprint and dietary quality at a food and dietary level?

RQ_{6b}: What are the biding nutrients in optimized diets designed to be water footprint reduced, nutritionally adequate, and cultural-acceptability-focused?

2.3. Research aims

The aims of the research are in line with the research questions: this dissertation's purpose is to create methodological pathways, results, conclusions, and theses based on this initial question.

(1) To estimate the possible reduction of dietary water footprint on the population-level based on diet optimization designed to be water-footprint-reduced, nutritionally adequate, and cultural-acceptability-focused.
(2) To estimate the possible reduction of dietary water footprint based on baseline dietary scenarios and its alternatives on the population-level.
(3) To estimate the main contributors to the total dietary water footprint among food groups and sub-groups on the population-level.
(4) To evaluate the health and dietary water footprint impact and their associations of baseline dietary scenarios and their alternatives on the population-level.
(5) To describe the characteristics of a water footprint-reduced, healthier, and cultural acceptability-focused diets on the population-level.
(6) To identify associations of the most consumed food items and categories based on their food-related water footprint and health benefits or risks on the population-level.
(7) To identify binding nutrients in a water-footprint friendly, healthier, and cultural-acceptability-focused diets on the population-level.

3. LITERATURE REVIEW

3.1. Sustainable nutrition

The Sustainable Development Goals (SDG) were created to address the threatening global challenge of population growth, depletion of natural resources, and climate change. In order to achieve SDGs, several action plans are focusing on the protection of the environment and natural resources and to keep human activity within the local and planetary boundaries (United Nations [UN], 2015; Vanham et al., 2019). The concept of sustainable nutrition is an approach that could contribute to the resolution of several food and environment impact-related SDGs, namely the 1st (no poverty), 2nd (zero hunger), 3rd(good health), 4th (quality education), 5th (gender equality), 12th (responsible production and consumption), 13th (climate Action) and the 2nd, 6th. and 7th that are linked by the Water-Energy-Food-Ecosystem (WEFE) nexus (Vanham et al., 2019). Besides, ensuring sustainable food and nutrition security is also a highly important aim in the EU (Rutten et al., 2018). It is a critically important issue since the food production contributes to the 20-30% of total anthropogenic greenhouse gas emissions (GHGE), 70% percent of total anthropogenic water use, and major cause of deforestation, land use, biodiversity loss, and water pollution (Fischer & Garnett, 2016). The definition and aim of a sustainable diet stand as the following: "*Sustainable Healthy Diets are dietary patterns that promote all dimensions of individuals' health and wellbeing; have low environmental pressure and impact; are accessible, affordable, safe, and equitable; and are culturally acceptable. The aims of Sustainable Healthy Diets are to achieve optimal growth and development of all individuals and support functioning and physical, mental, and social wellbeing at all life stages for present and future generations; contribute to preventing all forms of malnutrition (i.e. undernutrition, micronutrient deficiency, overweight and obesity); reduce the risk of diet-related NCDs; and support the preservation of biodiversity and planetary health. Sustainable healthy diets must combine all the dimensions of sustainability to avoid unintended consequences.*"(FAO and WHO, 2019). This definition immediately shows the holistic and complex nature of this approach, which breaks the paradigm of the previous attitude toward nutrition. Traditionally, the focus of "healthy diets" was solely on human health (including physical activity) and the prevention of chronic diseases regardless of their form and focus-population. They were based on known dietary factors, namely to discourage the consumption of foods and nutrients associated with the risk of developing diseases and the promotion of those that could prevent diseases (Fischer & Garnett, 2016; Mozaffarian & Ludwig, 2010). The status of these particular foods and nutrients is context-dependent, meaning that developing countries are typically suffering from micronutrient deficiencies while developed countries mainly battle with imbalance: over-consumption of nutrients as dietary risks and under-consumption of nutrients as protecting factors (FAO, 2019; Fischer & Garnett, 2016). For example, nowadays in the developed world, it’s a long haunted aim to reduce the prevalence of the non-communicable diseases (NCDs) that are the leading cause of death in those countries (IHM, 2019). These dietary factors are the high intake of sodium, total fat, trans-fatty acids, and saturated fatty acids, while the low intake of potassium, dietary fibers, calcium, and polyunsaturated fatty acids, or translated to foods: high intake of sweets, snacks, meat while the low intake of grains, vegetables and fruits (Institute for Health Metrics and Evaluation (IHM), 2019). The dietary recommendations aimed to reverse these trends of nutrient and food intake (Mozaffarian & Ludwig, 2010).

Sustainable nutrition as a concept has radically extended the focus of the "healthy diet" and includes factors that are above the human body if such distinction exists. Besides human health, these factors include the environmental, economic, and socio-cultural aspects of life, widening the definition of well-being related to nutrition. The evolution of food-based dietary guidelines started to integrate this idea and the first official (government-backed) and not official guidelines appeared worldwide showing us sustainable dietary patterns. Germany, Brasil, Sweden, and Qatar lead the way with official guidelines, while considerable steps have been done in Australia and the United States to involve sustainability, while quasi-official FBDGs came out in the Netherlands, the Nordic European countries, Estonia, United Kingdom and France. Besides, professional organizations, such as the British Dietetic Association publishing the "One Blue Dot"(The Association of UK Dietitians [BDA], 2018) and the Barilla Center for Food *&* Nutrition (BCFN) also created sustainable dietary guidelines (Fischer & Garnett, 2016). However, currently published FBDGs are still inconsistent in involving sustainability, especially regarding the environmental impact, however, the updated Mediterranean Pyramid is a good example involving all aspects, as well as the updated Hungarian FBDG that accounts for the environmental aspects too (Fernandez et al., 2021; Okostányér®, 2016). Based on these guidelines, the general characteristics of a "low environmental impact diet consistent with good health" can be described, however, adding that it's true in general but may change if put in a specific context. These aspects are:

- “Diversity – a wide variety of foods eaten.
- Balance achieved between energy intake and energy needs.
- Based around: minimally processed tubers and whole grains; legumes; fruits and vegetables – particularly those that are field-grown, "robust" (less prone to spoilage), and less requiring rapid and more energy-intensive transport modes. Meat, if eaten, in moderate quantities – and all animal parts consumed.

- Dairy products or alternatives (e.g. fortified milk substitutes and other foods rich in calcium and micronutrients) eaten in moderation.
- Unsalted seeds and nuts.
- Small quantities of fish and aquatic products sourced from certified fisheries.
- Very limited consumption of foods high in fat, sugar or salt and low in micronutrients e.g. crisps, confectionery, sugary drinks.
- Oils and fats with a beneficial Omega 3:6 ratio such as rapeseed and olive oil.
- Tap water in preference to other beverages – particularly soft drinks."(Fischer & Garnett, 2016)

The Double Pyramid published by the Barilla is especially pioneering, even so, it's globally adaptable and gives general and simple guidance, and backed up a tremendous amount (more than 1.000 publications) of research data on environmental impact (Figure 2.). Instead of the traditional one-dimensional (health) pyramid, there are two: a food (i.e. health) and an environmental pyramid that immediately shows the synergies and obstacles of these two dimensions. The overall picture seems simple, the plant-based food has a lower environmental impact and is the basis of the food intake pyramid so we should eat more of them, while the animal-based foods have a higher environmental impact and build up the middle and top of the food intake pyramid so we should eat less of them (Barilla Center for Food & Nutrition [BCFN], 2016a; 2016b). But as soon as we go into details, especially into food sub-groups such as fermented dairies versus cheese or red meat versus poultry, the details are contradictory that pointing to the overall conclusion that this synergy is not linear nor simple (Gazan, Brouzes et al., 2018; MacDiarmid, 2013; Perignon, Vieux, Soler, Masset, & Darmon, 2017; Vieux, Soler, Touazi, & Darmon, 2013), however, it exists as concluded by comprehensive works (Hallström et al., 2015; Jones et al., 2016).

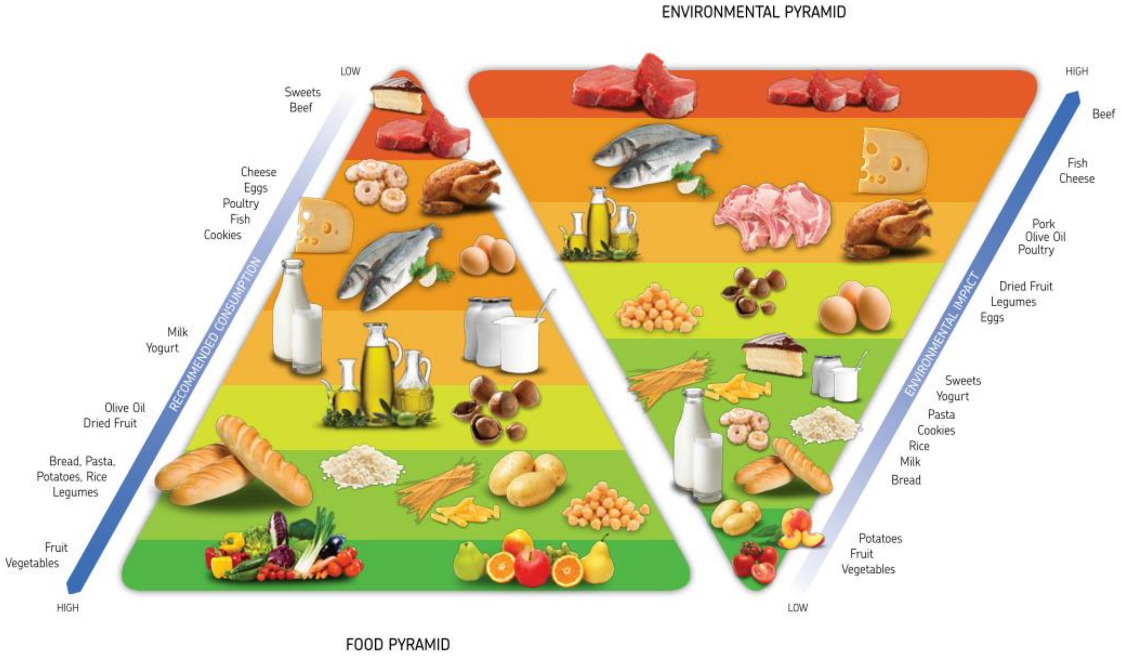


Figure 2: Double pyramid by Barilla Center for Food & Nutrition (BCFN, 2016b)

3.2. Dimensions, indicators, and metrics of the sustainable food system

According to Gustafson et al. (2016), the sustainable food system has 7 aspects that can be measured by numerous metrics: food nutrient adequacy (e.g. nutrient density score), ecosystem stability (e.g. land use), food affordability and availability (e.g. poverty index), sociocultural wellbeing (e.g. child labor), resilience (e.g. food production diversity), food safety (safety score) and waste and loss reduction (e.g. post-consumer waste). These categories well fit with complex definitions and the idea of sustainable nutrition, even though, the "food system" includes a wider range of levels than nutrition. These metrics are usually applied on a population or system level, especially since some metrics can only be calculated as such, for example, the food production diversity. Some metrics overlap with sustainable nutrition measurement and can be applied to one individual as well as to a population, it is for example the nutrient density score which could be a person's daily diet or a population mean value (Gustafson et al., 2016).

3.3. Dimensions, indicators, and metrics of sustainable nutrition

In the review of Jones et al. (2016), the measurement of sustainable nutrition was divided into 3 main categories: health (e.g. diet diversity), ecological (e.g. water use), and social aspects (e.g. food traditions) (Figure 3.). The most common metrics in the analysed studies (n = 113) were GHGE (63%), land use (28%), animal-based food intake (27%), and water use (common, but < 25%). These are mainly environmental impact indicators and a dietary factor meaning that the socio-cultural aspects are weighted less, harder to quantify or different metrics are used and each in a diverse way. While, in a review Gazan, Brouzes et al. (2018) concluded that the main dimensions of sustainable diet optimization studies are as follows: nutritional adequacy and cultural dimensions (included in all 67 studies), and economic and environmental impact metrics are commonly applied. In a "case study" of sustainable nutrition database compilation, Gazan et al (2018a) described the following sustainable nutrition dimensions: nutritional adequacy and food safety as health aspect sub-domains, cultural distribution of dietary intake in the population as the social aspect, economical affordability and environmental friendliness. Among environmental impact metrics, GHGE was calculated in the majority of studies besides water and land use as usually > 2 factors were accounted (Gazan, Brouzes et al., 2018). In another review on sustainable diet optimization, van Dooren (2018) described the constraints (based on metrics) applied in the optimization are 4 categories: economic, ecological, nutrition, and acceptability. In a review written by Hallström et al. (2018), there are studies that analysed the dietary quality and sustainability aspect of diets, in which GHGE also was applied in most of the studies, while nutritional or dietary quality was calculated in all analysed study.

The economic or affordability aspect is an often used dimension that is mostly defined by food prices as metrics (Gazan, Brouzes et al., 2018; van Dooren, 2018). They will be not discussed in detail, since they are not calculated in this dissertation. The detailed description of metrics applied in the dissertation will follow the classification of Jones et al. (2016): sociocultural, ecological, and health.

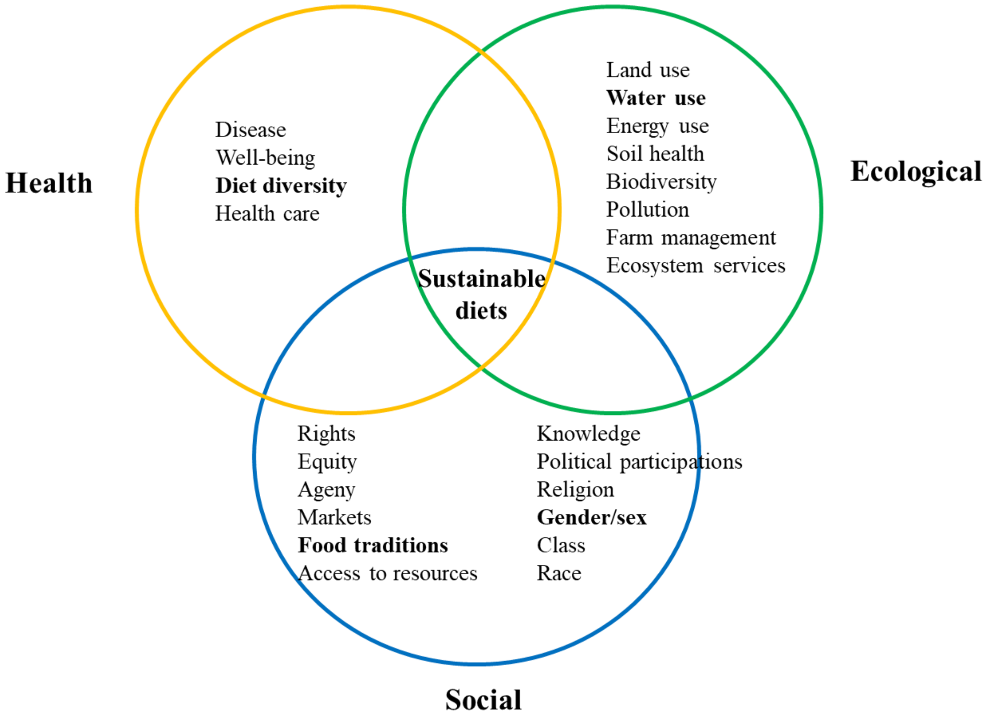


Figure 3.: Component of sustainable Nutrition, based on Jones et al. (2016), focused elements of this dissertation are highlighted

3.3.1. Cultural acceptability as sociocultural metric

Maybe the most problematic element is the "cultural acceptability" aspect which has nor definition neither consistent term. This refers to the adherence to the traditional food consumption and meals of the analysed population or person (Gazan, Brouzes et al., 2018), meaning that with a smaller dietary shift we can assume it is acceptable, leaning towards the "as small as possible" principle. However, there is no clear definition of what is "acceptable" and no metrics to measure it, thus the well-accepted method for this is to respect this aspect by staying close to the observed diet as much as possible. This way, the observed dietary pattern (i.e. food intake value in g/day/capita) serves as the proxy of "cultural acceptability"(Gazan, Barré et al., 2018; Gazan, Brouzes et al., 2018). Dietary pattern, by definition, is: "…the quantities, proportions, variety, or combination of different foods, drinks, and nutrients (when available) in diets, and the frequency with which they are habitually consumed" (United States Department of Agriculture [USDA], 2015). Based on previously described methods (Cleveland, Escobar, Lutz, & Welsh, 1993) French researchers were pioneering to put cultural acceptability in the very center of sustainable diet optimization, realizing that previous approaches caused a great dietary shift, sometimes excluding whole food groups from the observed diet that cannot be assumed to be acceptable by the population (Darmon, Ferguson, & Briend, 2003; Maillot, Vieux, Amiot, & Darmon, 2010; Perignon et al., 2016a; Vieux, Perignon, Gazan, & Darmon, 2018). They defined their optimization model with an objective function (Equation 1.) that minimizes the deviation from the observed diet. Vieux et al. (2018) applied this objective function (OF) in a study in which sustainable diet optimization was carried out for 5 European countries (France, the UK, Italy, Finland, and Sweden).

Equation 1.:

$$minimize\ f = \sum_{i=1}^{n} ABS\left(\frac{Q_{opt,i} - Q_{obs,i}}{Q_{obs,i}}\right)$$

where *i* is a food item, *n* is the number of available food items in the country and gender population modeled, Q_{opt} is optimized quantity, and Q_{obs} is the mean observed quantity.

Other sociocultural aspect includes gender equity, religion (rules on allowed foods), and knowledge of nutrition and population classes among others (Jones et al., 2016). As it seems, these are aspects difficult to quantify in the form of metrics, however, they are profoundly important in the tradition of meals and nutrition. Commonly, sex or gender are taken into account by describing different observed and modeled sustainable diets for men and women, adding that sex is used for the calculation of the biological need for nutrient intake, however, gender could be as well taken into consideration for considering eating habits.

3.3.2. Environmental impact as an ecological metric

Environmental impact is translated into several metrics that are sometimes described by different terms. For example, the most often used metrics GHGE can be described as carbon footprint, climate change, or climate impact, however, they mean the same as the greenhouse gas emission created by the production of 1 kg food (g CO2 eq. / kg food) (Gazan, Brouzes et al., 2018; Jones et al., 2016; Perignon et al., 2017). Environmental impact categories to measure sustainable nutrition classified by Hallström et al. (2018) are the followings:

(1) Climate: GHGE
(2) Use of natural resources: land use, water use, total resource use, raw materials,
(3) Emissions: sulfur dioxide emission, nitrogen emission, phosphate emission
(4) Biodiversity

From the environmental impact comes the concept of environmental footprint, a term that is based on environmental impact related to human activity. "*Footprints are indicators of the pressure of human activities on the environment. Footprint quantification is based on life cycle thinking along the whole supply chain (from producer to consumer, and sometimes to waste management) and aims to give a comprehensive picture of the quantified pressure. Each footprint focuses on a particular environmental concern, and measures either resource appropriation or pollution/waste* *generation, or both.*" (Vanham et al., 2019). Environmental footprints include a wide range of categories: ecological, carbon, water, land, energy, nitrogen, phosphorus, material, biodiversity, chemical, and ozone. Environmental footprints are tools to measure and quantify sustainability, so the SDGs could be achievable in the future (Vanham et al., 2019). As such, environmental footprints are often applied indicators of the environmental impact measurement of sustainable nutrition. In the analysis and optimization of sustainable nutrition environmental footprint metrics are matched with food items, since they are the basis of all calculations.

In this dissertation, the sustainable analyses and optimization focus on water footprint so this environmental footprint will be discussed in detail.

3.3.2.1. Water footprint

Food production is responsible for 70% of anthropogenic water use and is the major source of water pollution (Fischer & Garnett, 2016), while the access to water is limited regarding local and planetary boundaries (Vanham et al., 2019). Water, by nature, is essential not just for human biological needs but for safe food production. The reduction of freshwater use and water pollution is related to several SDGs and one element of the water-(Hoekstra & Wiedmann, 2014) energy-food-ecosystem nexus (Vanham et al., 2019). The intervention in one element affects the others, as we see food production and water use are multiply bonded together, so a sustainable diet that includes the water footprint reducing aspect is critically important for the future. The importance to consider the water footprint of humanity is more and more in the focus of research of future sustainability. In its latest country-specific recommendation, the EC highlights the importance of sustainable water management in Hungary, since the impact of climate change can considerably affect Hungary through floods and droughts, which makes the handling of water resources especially important (EC, 2022b). For the identification of intervention point to reduce the water footprint of animal- and plant-based foods production, water footprint (including green, blue, and grey water) is an indicator with great potential (Nagypál et al., 2019).

The water footprint is an environmental impact indicator (pressure of human activity) that measures both freshwater resource use (blue and green water) and the assimilation of waste water (grey water) (Hoekstra, 2017; Vanham et al., 2019; WFN, 2020). Practically, three types of water sum up the total value:

(1) Green water is mainly originated from precipitation and water stored in the root zone of the soil and incorporated, evaporated, or transpired by the plants. It is most important for agricultural, horticultural, and forestry food production.

(2) Blue water is sourced from ground or surface water and evaporated or incorporated into food

products or taken from one body of water to another. It is the most relevant for irrigation and industrial and domestic use.

(3) Grey water is the amount of freshwater used for diluting polluted water to meet legal quality standards; therefore, it is an indicator of water pollution. This footprint measures point-source pollution discharged to a freshwater resource directly through pipes or indirectly via runoff or leaching from the soil, waterproof surfaces, or other diffuse sources (WFN, 2020).

The water footprint concept was developed by Arjen H. Hoekstra based on the innovative idea to interpret water use in a supply chain thinking. This also meant to include green water in the analysis that is water used for agricultural production. Thus, this is based on the inclusion of indirect or virtual water, not just the direct use (blue water: irrigating, industrial and domestic use). Besides, the total water footprint value can include the grey water so it also accounts for the water pollution. Green and blue water are rather quantitative, while grey water is a rather qualitative indicator (Hoekstra, 2017). Previously, blue water is considered for sustainable nutrition studies, however, in the recent years, the inclusion of green water is supported and applied (Capone et al., 2013; Falkenmark & Rockström, 2006; Harris et al., 2020; Hoekstra, 2017; Hoff et al., 2010; Vanham, Hoekstra, & Bidoglio, 2013; Vanham, 2020). However, as Ansorge & Stejskalová (2022) argued, while the inclusion of all components is recommended, there should a special consideration for each element. The water footprint of food production is country and region-specific, so is the proportion of green and blue water in the total water footprint and the proportion of blue water footprint should be minimized (Ansorge & Stejskalová, 2022). In the case of Hungary, the proportion of blue water (59-176 l/day/capita) in the total water footprint (3941-4991 l/day/capita) is relatively small, falling into the smallest range in the global classification (Figure 4.). Consequently, the green water footprint makes up the majority (3303-7697 l/day/capita) of the total water footprint values of foods in Hungary (Harris et al., 2020).

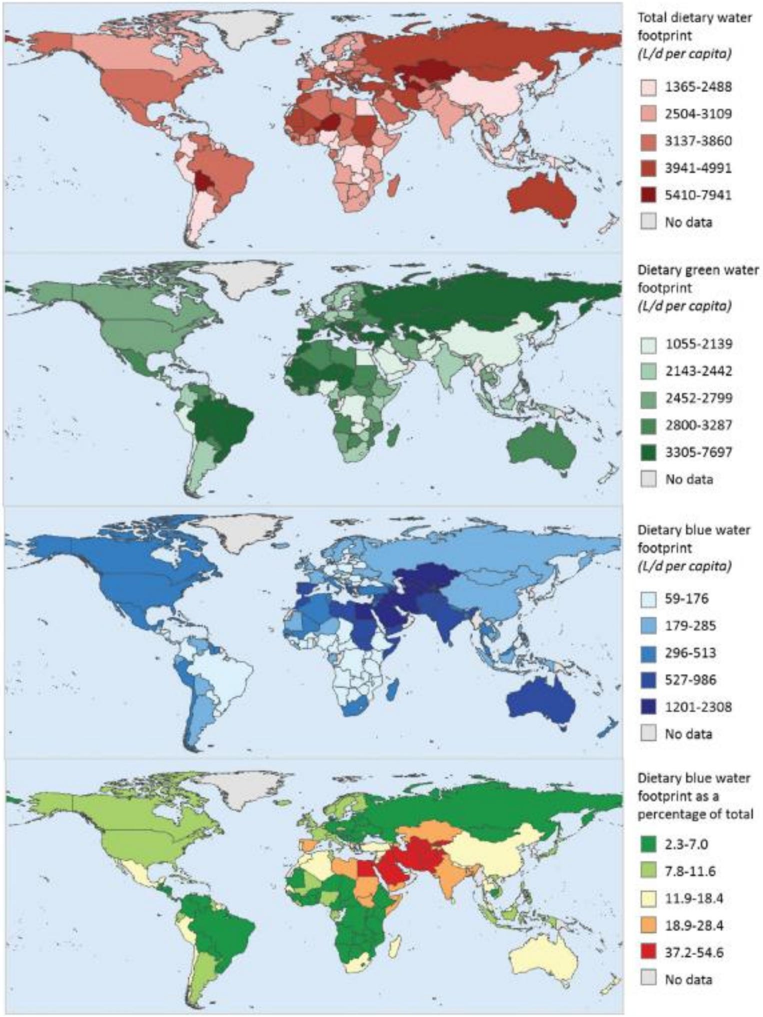


Figure 4: Global distribution of green, blue, and total dietary water footprint (Harris et al., 2020)

3.3.2.2. Calculation of dietary water footprint

Similar to other environmental impact indicator calculated in the Life Cycle Assessment (LCA) concept, there is two basic approaches to calculating the water footprint of food consumption: "bottom-up" and "top-down". In the "top-down" approach, dietary water footprint is calculated as total water footprint consumption within a region minus export of virtual water plus import of virtual water. In the case of the "bottom-up" approach, the intake amount of food products is multiplied by their water footprint value of them. The "bottom-up" approach is usually used in studies analysing dietary water footprint (Harris et al., 2020; Lares-Michel et al., 2021; Tom, Fischbeck, & Hendrickson, 2016; Vanham, 2020). When relating it to food products, water footprint measures the volume of water applied to produce a kg of food item including direct and indirect water use such as the embodied fresh water to produce plant-based feed for livestock (Hoekstra, 2017). Thus, the unit usually calculated in the studies of sustainable nutrition is l / kg or l of a food item or l / day /capita in the case of a daily diet of a person or the average daily intake of a population (Chaudhary & Krishna, 2019; Harris et al., 2020; Jalava et al., 2014; Vanham, Hoekstra & Bidoglio, 2013; Vanham, Mekonnen, & Hoekstra, 2013; Vanham, 2020). The database of the Water Footprint Network (WFN) that is based on the first water footprint standard includes the country and region-specific green, blue, and grey water footprint of plant-based and animal-based foods. For farm animals and derived products, it includes data for grazing, mixed, and animal husbandry water footprint data (Mekonnen & Hoekstra, 2010a, 2010b; Water footprint Network [WFN], 2020). It is an advantage of this database that water footprint is region-specific due to different weather conditions, water resources, and industrial technologies, however, it also holds a global dimension due to virtual water. In most studies, country-specific data is considered, but food consumption is not only based on local production but also on export food products from different countries, in which the virtual water is already embodied that could be thousands of liters of water for a kg of animal-based product.

3.3.3. Dietary quality as a health metric

The health aspect of sustainable nutrition is commonly expressed as dietary quality, they are sometimes separately classified, however, they are logically related and commonly exchanged (Gazan, Brouzes et al., 2018; Gustafson et al., 2016; Hallström et al., 2015, 2018; Harris et al., 2020; Jones et al., 2016) terms. If the health aspect (impact or outcome) is calculated, it can only be derived from dietary risk or protecting factors that are the characteristics of a person or population's dietary pattern. The dietary factors and health outcomes can be related to the database of the Global Burden of Disease (GBD) (IHM, 2019), where health outcome is quantified (Springmann et al., 2018). For example, a high intake of processed red meat is a dietary risk factor for the development of NCDs, the higher a diet in processed red meat, the worse the health outcome there is. Another common method to measure dietary quality is comparing diets or scenarios to food-based or nutrient-based dietary guidelines since these dietary guidelines are designed to represent health nutrition that prevents diseases, usually NCDs (Hallström et al., 2015, 2018; Harris et al., 2020; Jones et al., 2016). The assumption is reasonable that the closer a diet to the dietary guidelines, the better health outcome it provides. Dietary quality is usually calculated in a one or two (beneficial and non-beneficial values) dimensional score that is either based on nutrient intake or food quantity values of a diet compared to recommended intake values (RDIs) (e.g. RDIs published by the European Food Safety Authority (EFSA), (EFSA, 2017) of nutrients or FBDGs (e.g. smart plates (Fischer & Garnett, 2016; Hallström et al., 2018). These scores are the so-called "dietary quality scores" (referring to a whole diet or meal) or "nutri-scores" (referring to foods). They will be described in detail in section 3.5., as important sustainable nutrition analysis tools.

Dietary data and dietary shift

Dietary data is the basis of all sustainable nutrition analysis, it represents the "baseline" dietary pattern or the "observed diet" as it is often called. It can refer to a focused population or a sole individual. In the case of prior, the average population is considered as observed diet, often divided by sex/gender (resulting in two average observed diets). In the case of diet optimization, the approach can be population- or individual-based which will later be discussed in detail in section 3.8 Gazan, Brouzes et al., 2018; van Dooren, 2018). Consequently, the starting point of sustainable nutrition analysis and optimization can be a person's daily diet or typical national food consumption. In sustainable nutrition, the traditional methods of recorded dietary data (Shim, Oh, & Kim, 2014) and estimated food consumption or supply are applied for further analysis (Gazan, Brouzes et al., 2018; Hallström et al., 2018; Harris et al., 2020; Jones et al., 2016; Vanham, 2020). The main distinction comes from the approaches (Fardet & Rock, 2014) that is similar to "bottom-up" (dietary records) when the calculation starts from individuals and then is averaged for a population or the "top-down" approach when the national supply is divided by the population number. Accounting for the scale and type of data, the following classification can be made:

(1) Population-level (“top-down”) : national food supply data
(2) Individual-level (“bottom-up”): recoding of the food consumption or diet
    a. food frequency questionnaire
    b. 24-hour dietary recall recall
    c. dietary records (Shim et al., 2014)

The food supply data is most commonly acquired from the database of the Food and Agricultural Organization of the United Nations (FAO), the so-called “Food Balance Sheet” (FBS), where national food supply can be downloaded in the form of kg (of food item) /year/capita among others (Food and Agricultural Organization of the United Nations [FAO], 2020). As the term suggests, it is not direct consumption data, but an estimated amount of available food for one person in a year. It also considers raw or staple foods, so consumption is often estimated by using correction values to consider the removal of indigestible parts such as vegetable peels or animal bones (Vanham, Hoekstra & Bidoglio, 2013). With this transformation, the food supply is widely accepted as the proxy for food consumption (Vanham, 2013). An advantage of it is that its relatively simple to match food supply data with other data types such as national emission values, besides, it makes it reasonable to compare the characteristics of different nations (Harris et al., 2020; Jones et al., 2016; Vanham, Hoekstra, Bidoglio 2013, Vanham, Mekonnen & Hoekstra 2013). In the case of dietary records, the survey design is often different in countries, so it is almost impossible to directly compare, however, a solid advantage of it is that it's more accurate by the nature of directly analysing the "details" (i.e. individuals). However, comparing the results of sustainable nutrition analysis originating from the two profoundly different data types can be misleading (Vanham, 2020) but still cannot be avoided due to the methodological differences in this field (Gazan, Barré et al., 2018; Gazan, Brouzes et al., 2018, 2018; Hallström et al., 2015, 2018; Jones et al., 2016).

The dimension of dietary data is predominantly in the unit of g (of food item)/day/capita Gazan, Brouzes et al., 2018; Hallström et al., 2018; Harris et al., 2020; Jones et al., 2016; van Dooren, 2018). In the case of individual scale diet recording, it is considered as such dimension from the start, however, supply data is usually in kg (of food item) /year/person (FAO, 2020), so a transformation to g (of food item)/day/capita is usually made.

As mentioned in section 3.3.1. (cultural acceptability), dietary data serve as a reference point for the observed diet so the proxy of cultural acceptability. This way, the baseline of cultural acceptability can be quantified and used as a metric. From this follows another important term in sustainable nutrition, the "dietary shift" or "dietary change". The dietary shift is the change between the observed diet and other dietary scenarios or optimized diets. Since diets can be described by the combination and quantity of foods for a daily intake, it is usually expressed as g / day /capita or the relative value of it in percent. It is usually analysed by foods or food groups, however, an overall quantity change can be as well calculated that is based on the objective function to minimize deviation from the observed diets (Equation 1.) (Chaudhary & Krishna (2019; Meltzer et al., 2019; Perignon et al., 2016a; Vieux et al., 2018):

3.4. Compilation of sustainable nutrition database

According to Gazan et al (2018a), the database building of sustainable nutrition can be distinguished into 3 different phases: (1) data collection, (2) definition of the list of foods (food categorization), (3) and data compilation. In the phase of data collection, the relevant food dimensions are selected and quantified by metrics measuring it, for example the ecological aspect, the water footprint is selected as metrics with a real value. As mentioned before, the "obligatory" data is the dietary data that will give the axis of the database. The second phase is practically the categorization of foods, in other words making the list of foods. Depending on the dietary type described earlier, these data can be in food items, food sub-groups, groups, or categories. Very often, food items are aggregated in a less specific category, for example, Gouda and mozzarella cheese will be classified as fatty or processed cheese. The aggregation is based on similarity and the original and aggregated food group nutrient composition should show a strong correlation (Perignon et al., 2016b). The most common classification is based on food groups typically forming FBDGs (Fischer & Garnett, 2016; Harris et al., 2020; Jones et al., 2016; Okostányér®, 2016; Vanham, 2020). In the third phase, the list of foods is to be matched with the selected metrics of sustainable nutrition. In the simplest case, if the metrics related to the food item and the food list item are equal, then they are directly related. However, if there are more matches for compilation the followings option can be used: (1) the value attached to the food group will be the population intake weighted average of related foods (e.g. vegetables food group as the average values of lettuce, cucumber, tomatoes, etc.), (2) one most commonly consumed representative food item is chosen (e.g. liver for offals food group) and (3) a random related food item to be selected. If there is no matching metrics for a food item, another data source should be searched for. This database or list of foods matched with sustainable nutrition metrics will be the input for statistical and dietary scenario analysis and diet optimization(Gazan, Brouzes et al., 2018).

3.5. Scores as assessment tools for sustainable nutrition

Almost all dimensions of sustainable nutrition can be measured with indexes and scores as metrics (Gustafson et al., 2016), however, it is most often applied to the health aspect, directly the dietary or food quality. Nutriscore refers to foods (Darmon, Vieux, Maillot, Volatier, & Martin, 2009; Fern, Watzke, Barclay, Roulin, & Drewnowski, 2015; Maillot, Darmon, Darmon, Lafay, & Drewnowski, 2007), while dietary quality score (DQSs) refers to whole diets, however, meals can be measure as well (Hallström et al., 2018). Dietary quality scores are quantified based on the proportion of the nutrient intake of diets compared to the RDIs or the fulfillment of criteria based on nutrient intake (e.g., whether a diet consists of 90 mg vitamin C or not) or FBDGs (e.g. whether a diet includes 500g vegetables or not). Nutriscores, based on similar logic is calculated by comparing the nutrient composition of foods to the daily RDIs (Hallström et al., 2018). In the case of Nutriscores, the functional unit of 100g, 100 kcal or 1 typical portion/food can be applied, however, there is no consensus on which is the best. Even though there are pros that 1 portion would be reasonable to consider over 100g or 100 kcal, it is often subjective or differs by data source and is hard to calculate (Hallström et al., 2018; Masset, Vieux, & Darmon, 2015). The dietary scores can include only a few nutrients accepted as quality indicators or a number of them (Hallström et al., 2018). Dietary factors proven as protective for health and commonly under-consumed in the population will be classified as “positive”, “beneficial” or “qualifying”, while nutrients that are associated to health risks and commonly over-consumed in the population will be classified as “negative”, “non-beneficial” or “disqualifying”(Hallström et al., 2018). For example, saturated fatty acids (SFA) are overconsumed in the western diets and this level of intake is proven to be linked to NCDs, so this nutrient will be classified as dis-qualifying in each case (Hallström et al., 2018). DQSs can be a one-dimensional score (integrated qualifying and disqualifying nutrients) or analysed separately. For example, Perignon et al. (2016a) applied the Maximum Adequacy Ratio (MAR) – positive – and Mean Excess Ratio (MER) – negative – score system that is based on the proportion of nutrient intake from diets and RDIs and maximum recommended values (MRVs), (Equations 2-3.). The principle of these algorithms is widely used in this field of research:

Equation 2.:

$$MAR = \frac{1}{n} \sum_{bn=1}^{n} \frac{Q_{bn}}{RDA_{bn}} * 100$$

where *MAR* is the mean adequacy ratio, Q_{bn} is the daily quantity of each beneficial nutrient (*bn*) and RDA_{bn} is the corresponding recommended intake for this nutrient.

Equation 3.:

$$MER = (\frac{1}{n} \sum_{ln=1}^{n} \frac{Q_{ln}}{MRV_{ln}} * 100) - 100$$

where *MER* is the mean excess ratio, Q_{ln} is the daily quantity of each nutrient to limit (*ln*) and MRV_{ln} is the corresponding maximum recommended value for this nutrient (Perignon et al., 2016a).

Lukas et al (2016) also developed an integrative sustainable nutrition score system, in which they included four metrics for two sustainable nutrition dimensions: (1) health indicators: energy intake (kcal), sodium intake (g), dietary fibers (g), saturated fatty acids (g) and (2) environmental indicators: material footprint (g), carbon footprint (g CO_2 eq.), water footprint (l) and land use (m^2).

3.6. Statistical analyses on sustainable nutrition

While statistical and correlation analyses can be as well applied to all metrics of sustainable nutrition, it is usually focused on the health-environment dimensions besides the economic aspect. This work concentrates on the health-environment axis as well, so they will be introduced. The environmental impact is usually calculated as GHGE, while water and land use also often appears in such studies as environmental impact measure (Hallström et al., 2015, 2018; Jones et al., 2016). The health aspect is measured by either nutrient intake (of diets) or composition (of foods) or "nutriscore" or DQSs. Among nutrients, the energy intake (kcal/person/ day from diet) or energy density of foods (100g/kcal) is the most common (Darmon et al., 2003; Drewnowski et al., 2015et al., 2016a; van Dooren, Douma, Aiking, & Vellinga, 2017; Vieux et al., 2013). These dimensions can be analysed separately, then correlation analyses might be done or one integrative dimension can be created (Hallström et al., 2018) Masset et al. (2015) develop a score integrating food price, related GHGE and SAIN:LIM nutriscore system (consist of both positive and negative nutrients) (Masset et al., 2015). Similarly, van Dooren et al. (2017) integrated food-related GHGE with nutritional characteristics in a sustainable diet measuring index (Sustainable Nutrient Rich Foods index (SNRF)).

3.7. Dietary scenarios in the field of sustainable nutrition

Dietary scenario analysis is the most commonly applied approach to analyse the theoretical shift toward more sustainable nutrition besides diet optimization. Dietary scenarios are technically the combination of foods with related quantity values. The axis of dietary scenario analysis is usually, the "baseline", "original" or – most commonly – the "observed" diet (Hallström et al., 2015; Harris et al., 2020; Jones et al., 2016; Vettori et al., 2021). As described in sections 3.3.1. and 0., the observed diet, thus the scenario is based on the population mean food intake data. The structure and food categorization differ according to input data type and database. Based on the observed scenarios, different scenarios can be created by changing the combination of foods in quality and/or quantity according to the aims of the study. The most common patterns to create scenarios are based on healthy dietary guidelines (Okostányér®, 2016), preventive dietary recommendations (e.g. cardioprotective diet (Downs & Fanzo, 2015), or sustainability-focused trends: reduced meat-content, vegetarian or vegan (Hallström et al., 2015; Harris et al., 2020; Jones et al., 2016). Besides, scenarios based on alternative diets (e.g. ketogenic diet (Röös, Karlsson, Witthöft, & Sundberg, 2015) or Mediterranean diet (Sáez-Almendros, Obrador, Bach-Faig, & Serra-Majem, 2013). The concept of dietary scenario analyses is to compare the baseline scenario to the different alternative scenarios by evaluating the environmental and health impact from an integrative aspect. This impact analysis is generally as follows:

(1) Environmental impact analysis

Generally, GHGE consequences were the most often calculated environmental impact, followed by land use and water use. Some studies concentrate on a sole environmental footprint, such as the water footprint, and some analyse more than one. The results are understood as an increase or reduction in the environmental impact categories, most often expressed as in percent, thus different studies can be compared (Hallström et al., 2015; Jones et al., 2016; Scarborough, Allender, Clarke, Wickramasinghe, & Rayner, 2012). In the case of the water footprint, green, blue, and total water footprint can separately or solely be analysed (Harris et al., 2020).

(2) Health and dietary impact analysis

As described in section 3.3.3. dietary quality is a sub-domain of the health dimension of sustainable nutrition. The former is the most common metric in sustainable nutrition analysis, while the latter appears more rarely as direct analysis of health outcomes, such as the quantified change in mortality or disease adjust life years of the given population (Chen, Chaudhary & Mathys, 2019 Springmann et al., 2018). Besides, in the case of dietary scenarios based on healthy or preventive dietary guidelines are assumed to be a positive health outcome by the nature of these dietary guidelines. More precisely, dietary or nutritional quality are the metrics to be quantified in most cases. This can be done by comparing the nutrient content of scenarios to RDIs, creating DQSs, or comparing the amount of food groups to FBDGs (Hallström et al., 2015, 2018; Harris et al., 2020; Jones et al., 2016).

3.8. Diet optimization in the field of sustainable nutrition

Diet optimization is well established and proven method to resolve diet problems. The methodology is originated decades back in time and as soon as the field is sustainable nutrition appeared, this method was adapted to it. The possibilities to apply it and resolve different problems limitless (Gazan, Brouzes et al., 2018; van Dooren, 2018). The question about what are the best model, approach, and parameters is always "ad hoc" and case-specific.

Diet optimization is based on quadratic or linear programming (LP). While quadratic programming (QP) is known to have the advantage to minimize change on a population level better than LP, there is a good alternative in LP, by adjusting the objective function to minimize the relative deviation (in percentage from the observed diet (Equation 1). This OF facilitates larger variation in fewer foods, so keeping more foods in the outcome can make a diet more diverse, especially when several foods have initially low intake as input (Gazan, Brouzes et al., 2018). LP is more widely used in sustainable diet optimizing studies and since this dissertation also concentrates on LP, it will be discussed in detail. In LP, the aim is to find the optimum value (minimum or maximum that is relevant for the problem) of the linear equation. This function is conditional on several constraints defined as inequalities. The basic mathematical idea behind this method is that "the various relationships between demand and availability are linear" (van Dooren, 2018). Objective function in diet optimization (Equation 4.) (van Dooren, 2018):

Equation 4.: $$f = c_1 x_1 + \ldots + c_n x_n$$

As Figure 5. shows, sustainable diet optimization is run on 3 basic parameters: (1) decision variables, (2) constraints, and (3) an objective function (OF). In the case of diet optimization, decision variables are the set or combination of foods (with a related observed intake value), the possible structure and classification of them is described in section 0. in detail. The result of diet optimization will be a new combination of foods, in other words, the optimized diet. While the option for the type and number of constraints is almost infinitive (Gazan, Brouzes et al., 2018), the most typical sustainable nutrition metrics for constraints are (1) nutritional adequacy (e.g. RDI values), (2) diet cost (as economic dimension), (3) cultural acceptability (staying close to observed diet as much as possible) and (4) ecological dimension (e.g. water footprint) (van Dooren, 2018). The possibilities for the OF is also countless, however, it most often either aims to lower (1) environmental impact, (2) deviation from the observed diet (3) or diet cost (Gazan, Brouzes et al., 2018; van Dooren, 2018; van Dooren et al., 2017). The OF should be defined by the aim of the study, for example, "What is the lowest cost possible for a healthy diet?", "What is the lowest water footprint possible for a healthy diet?" "What is the minimum deviation from observed diet possible for a healthy diet and environmentally friendly diet?”(Gazan, Brouzes et al., 2018).

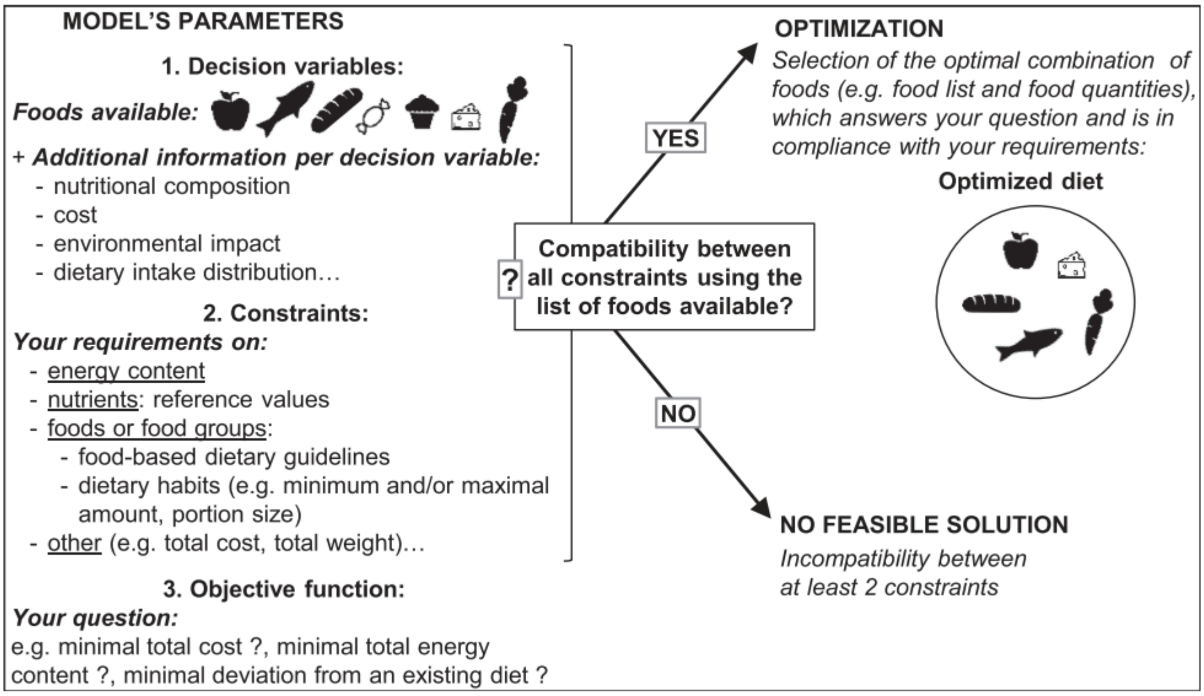


Figure 5: Diet optimization model's parameters (Gazan, Brouzes et al., 2018).

The focus of diet optimization can be either population- or individual-based that is depending on the number of diets. In the case of population-based studies, the observed diet provides the decision variables of the model which is the mean intake of the population (n = 1) (Gazan, Brouzes et al., 2018; Perignon et al., 2016a; Vieux et al., 2018). It is often separated by sex/gender or age group but the basics are the same only that more population class is accounted for, however, all with one average diet. In the case of the individual-based optimization, the model is run for all included diets that can be as much as a representative sample for a national study (n = ~1500-2000). From this follows that individual-based studies are suitable for statistical analyses while population-based studies are not (Gazan, Brouzes et al., 2018; Maillot et al., 2010; Maillot, Vieux, Delaere, Lluch, & Darmon, 2017). The possibilities also depend on the data types, while a national food supply will only give an average observed supply value, a national dietary survey can provide detailed data on individuals. Besides, obviously, diet optimization can be a case study as well, when only one individual diet is modelled.

3.8.1. Comparison of dietary scenario analysis and diet optimization: an inverse logic

The very central concept of sustainable diet studies is to define a dietary shift that is healthier than the baseline and relieves the environmental burden. In the case of dietary scenario analysis, this dietary shift is pre-defined, while in the case of diet optimization it is a result of the model, thus it is less biased and can lead to conclusions that are not hidden by the pre-assumption of dietary guidelines (Gazan, Brouzes et al., 2018; Hallström et al., 2015; Harris et al., 2020; Jones et al., 2016; van Dooren, 2018). Often, pre-defined scenarios exclude whole food groups by the start (e.g. vegetarian scenarios) which is more problematic to assume to be culturally acceptable than keeping all food groups consumed by the population (Vieux et al., 2020; Vieux et al., 2018). Another difference is the adjustment of the environmental impact reduction and nutritional adequacy goals: in diet optimization, they can be pre-defined (Gazan, Brouzes et al., 2018; van Dooren, 2018), while in the case of dietary scenario analyses, they can be only measured as output by impact analyses. An exception for that is the health aspect that can be pre-defined in the case of scenarios if it is based on healthy dietary guidelines (Hallström et al., 2015; Jones et al., 2016). However, any other aspect of sustainable nutrition can be defined in scenario analyses. From this follows, that the outcome analysis is different by nature between dietary scenario analysis and diet optimization. In the case of diet optimization, the dietary shift is the main result beside other metrics that were not pre-defined, for example, if GHGE reduction is set as a constraint we pre-defined that it should be at least – 30% or more, while if it set as the objective function, the amount of reduction will be an outcome of the model. In the case of dietary scenario analysis, the outcome will be further processed as environmental, health, or dietary impact. The number of options to create dietary scenario analysis is quite limited, basically, the alternative scenario is the input to be changed, while the option in the case of diet optimization is almost infinite, including what to include in the input or output, what dimension to control by constraint and that what we prioritize as an objective function (Gazan, Brouzes et al., 2018; van Dooren, 2018). On the other hand, the result of diet optimization can be infeasible that requires the post-definition of parameters that can be just as biased as alternative dietary scenarios (see Figure 6.).

It is important to add, that dietary scenarios - often called - can be inputs for diet optimization models as well, however, in this case, it does not refer to a pre-defined dietary shift (combination of food) but to different decision variables (e.g. leaving out meat from vegetarian diets) constraint or objective function. In the work of Perignon et al. (2016a), for example, one scenario only limited the RDIs for macronutrients, while the other one controls the RDIs of minerals and vitamins as well, while in the study of Jalava et al. (2014) the scenarios represented a stepwise reduction in animal-based proteins.

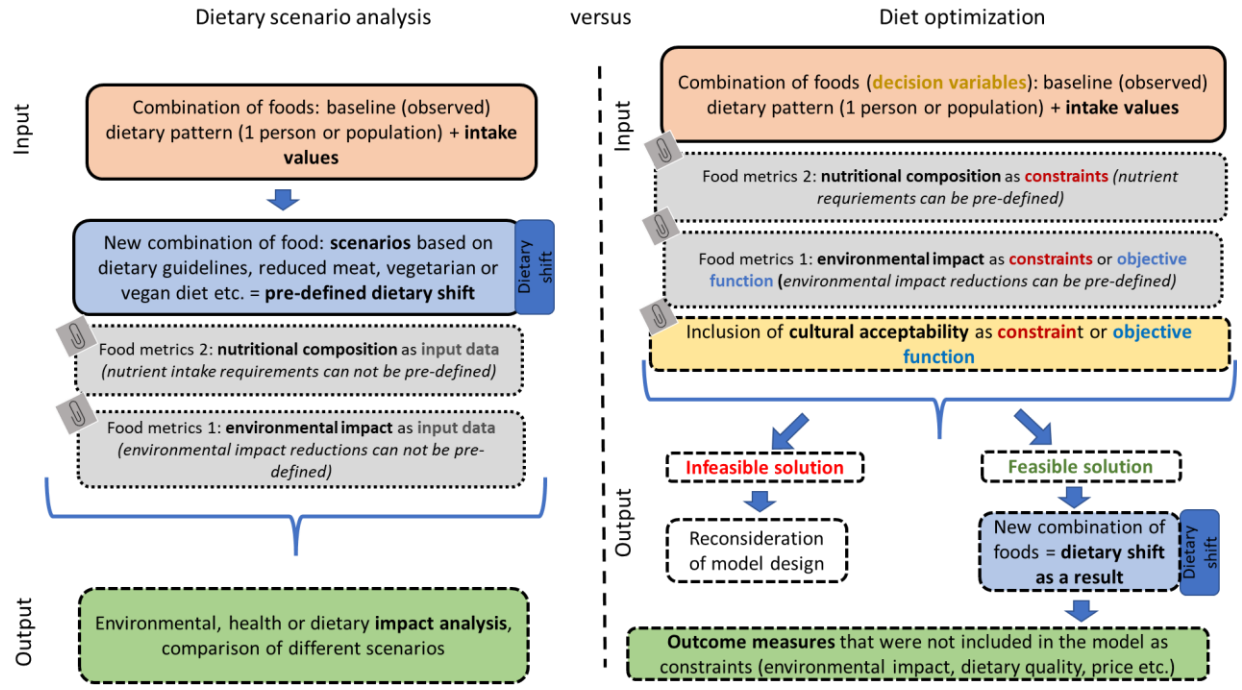


Figure 6: Comparison of diet optimization and dietary scenario analysis: a logical schematic figure (own edition)

3.9. Results of previous studies

3.9.1. Association of healthiness and environmental impact of nutrition

Alessandra (2014) evaluated the relationship (regression analysis) between Mediterranean Adequacy Index (MAI) as DQS and carbon, ecological, and water footprint. It proved a "clear relationship" in the case of all the environmental impact categories, meaning that the lower MAI was associated with higher environmental footprints. It means, that adherence to the Mediterranean diet can have a beneficial effect on sustainability. Tepper, Kissinger, Avital & Shahar (2022) also concluded that individual diets from the Israeli population with higher dietary quality and sustainability (higher Mediterranean Diet Score, Sustainable Healthy Diet and Eat-Lacet Score and lower GHGE and land use) tend to be higher in blue water footprint. Van Dooren et al. (2017) found a correlation between low food-related GHGE and positive nutritional characteristics. Food-related GHGE positively correlated with saturated fatty acids (SFA), trans-fatty acids (TFA), sodium, energy density, animal protein, and total protein. Except for the latter, they are negative dietary factors in excessive amounts, thus this positive correlation means an indicator of burden to both environment and health. Drewnowski et al. (2015) evaluated the association between food-related GHGE of 100g food and kcal/100g (i.e. energy density) of foods. They found that in general, higher food-related GHGE correlated with higher nutrient density, especially in the case of animal-based products that had the highest food-related GHGE value. Grains and sweets were low in both food-related GHGE and nutrient density, while high in energy density. On the contrary, in the analysis of self-selected diets among the French population, Vieux et al. (2013) found that the diets with the highest nutritional quality have significantly higher dietary GHGE (despite the high amount of plant-based foods) while diets with the lowest nutritional quality have significantly lower dietary GHGE. It leads to the conclusion that the "healthier" diet is not necessarily more environmentally friendly. In another French population study on sustainable nutrition (n = 1918), Vieux, Darmon, Touazi, & Soler (2012) found a significant positive correlation between dietary GHGE and daily energy (kcal) intake for the whole a sex-separated (men and women) samples too.

Similarly, in an Australian sustainable nutrition population study, Hendrie et al. (2016) found a positive significant correlation between the total energy intake (kcal) and dietary GHGE, pointing out that meeting an individual's energy requirement would lower the dietary GHGE besides adherence to healthy dietary guidelines and improving dietary quality. To classify "sustainable" and "non-sustainable" food, Saarinen, Fogelholm, Tahvonen, & Kurppa (2017) developed a nutrient index score that includes both nutritional and environmental aspects. They carried out correlation analyses based on food items (n = 29), where they found that dietary GHGE positively correlates with protein and zinc, besides negatively with folate. They also analysed the correlation between nutrient index scores and dietary GHGE, where they found very low (in the case of negative nutrient sub-score) or no linear relationship. In a population study (n = 395), Lares-Michel et al. (2021) proved correlation between dietary energy intake (kcal/capita/day) and dietary water footprint (l/day/capita) at a significant level ($p < 0.05$) (Figure 7.).

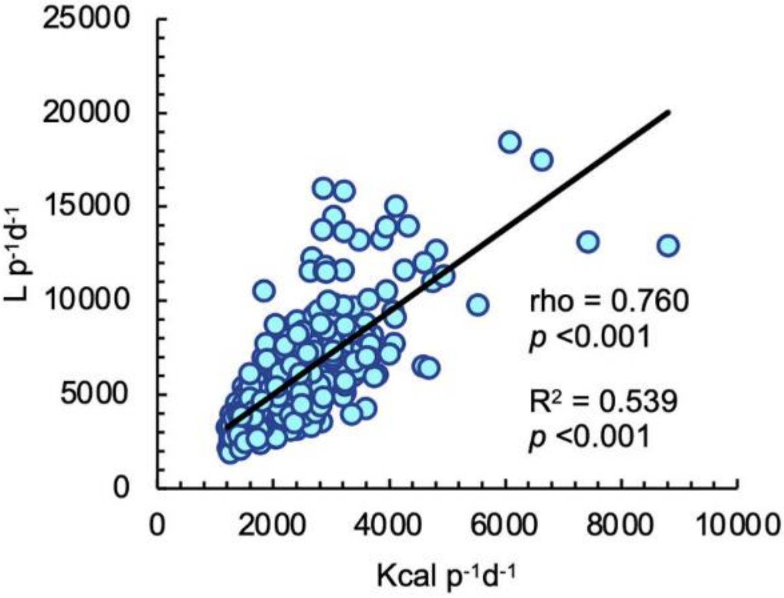


Figure 7: Linear regression between dietary energy intake (kcal/capita/day) and dietary water footprint (l/capita/day) in a Mexican population study (Spearman's rho, significance level at $p \leq 0.05$) (Lares-Michel et al., 2021)

3.9.2. Health and environmental – especially water footprint - benefits of sustainable focused-dietary changes

In studies analysing environmental impact reduction, the number of accounted environmental categories differ. Some studies concentrate on the insights of one environmental impact category, while others try to catch a more holistic picture by including more environmental impact categories in the analyses (Gazan, Brouzes et al., 2018; Hallström et al., 2015; Harris et al., 2020; Jones et al., 2016; Vettori et al., 2021, van Dooren, Marinussen, Blonk, Aiking, & Vellinga, 2014). Since this dissertation mostly concentrates on water footprint, only the major findings will be discussed about other environmental categories, while more details about water footprint. In a review of 14 sustainable nutrition studies, Hallström et al. (2015) found that compared to the observed diet considerable dietary GHGE reduction can be achieved:- 25-55% with vegan, - 20-35% with vegetarian, and - 0-35% with the healthier dietary scenario. Besides, they found that even more reduction is possible in the case of land use (vegan: -50-60%, vegetarian -30-50%, healthy diet (-15-50%). Steenson & Buttriss (2021) concluded similar values based on the review of 29 studies; with a dietary shift to recommended healthy diets with more plant-based food and less animal-based foods, a ~20-50% dietary GHGE and land use reduction is possible. In a country-specific, global modeling analysis, Springman et al. (2018) found that the replacement of animal-source foods for plant-based foods could reduce dietary GHGE by 84%, however, increase freshwater use (blue) by 16%, besides increasing nutritional quality and lower premature mortality. Alessandra

(2014) evaluated the diets of different European countries and concluded that 1 unit increase in MAI could result in a 20-25% decrease in carbon, ecological, and water footprint. Based on the food consumption pattern in the United States, Tom et al. (2016) created 3 scenarios to analyse the environmental impact. In the first scenario, energy (kcal) was adjusted to recommended for normal weight and the energy use, blue water footprint, and GHGE decreased by ~ 9%, in the second scenario they changed the pattern to the recommended without energy adjustment resulting in a 43% increase in energy, 16% in blue water footprint and 11% in GHGE. The third scenario was created by both energy and food pattern adjustment to recommend that also resulted in an increase in energy use (38%), blue water use (10%), and dietary GHGE (6%). Chaudhary & Krishna (2019) applied non-linear diet optimization for 152 countries with an OF to minimize departure from the country-specific observed diet to a more "sustainable diet", in the case of Hungary it resulted in a -40% dietary GHGE, -15% cropland use, - 15% nitrogen application, -21% phosphorous application and + 12% fresh water (blue water) use with 45% dietary.

Regarding studies focused on water footprint reduction, Harris et al. (2020) estimated in a meta-analysis that dietary shift could result in up to 25.2% total, 26.1% green, and 11.6% blue water footprint reduction with no animal-based foods, ~ 18% in reduced animal-based food scenarios, while around ~ 6% total, green and blue water change with the shift to “healthy diets”. Jalava et al. (2014) using QP resulted in a -100 – 0 l/day/capita blue water and -500 – -1000 l/day/capita green water reduction by shifting from the original diet to healthier for Hungarian consumers. On the global level, the dietary shift from the original to the recommended diet resulted in -6% in green water footprint, while -4% in blue water footprint. In the case of the Eastern region of Europe, Vanham, Hoekstra, & Bidoglio (2013) estimated a -11% reduction in total water footprint by shifting to a healthy diet scenario and -27% shifting to a vegetarian diet compared to the observed diet. Comparing the current Italian diet to an adequate Mediterranean diet, Capone et al. (2013) found that this dietary shift would lower the dietary water footprint by 69.9%. Hess, Andersson, Mena, & Williams (2015) calculated blue water footprint change of 5 alternative healthier scenarios compared to the observed UK food consumption patterns and only found a slight change in blue water use (-3 - +2%). In an Indian population study based on sustainable diet optimization, Milner et al. (2017) estimated a -30% blue water footprint reduction while satisfying the dietary guidelines and respecting cultural acceptability. Scheelbeek et al. (2020) estimated that the adherence to the Eatwell guide would provide only a 4-7% reduction in blue water footprint. Vettori et al. (2021) concluded that the vegetarian and vegan dietary scenarios could be the best solution to reduce dietary water footprint, however it is not clear which one is the more adequate.

3.9.3. The possible dietary shift towards a more sustainable nutrition

In the case of dietary scenario analyses, the dietary shift is pre-defined (most commonly as vegan, vegetarian, reduced meat, or "healthy" dietary scenarios) (Hallström et al., 2015; Jones et al., 2016) as described in section 3.7., so the results of optimization studies will be discussed. In the review of Steenson & Buttriss (2021) on sustainable nutrition studies, they found that the plant-based food groups (fruits, vegetables, pulses, nuts, whole grains, and roots) besides lower meat content were typically beneficial in the environment-health synergy. In optimization studies, the change in eggs and milk and dairy food groups was inconsistent, due to their good nutrient profile but a considerable environmental burden. The high fat/salt/sugar content food groups that are usually recommended to be limited in dietary guidelines (Fischer & Garnett, 2016; BCFN, 2016b) were profound contributors to environmental impact, meaning they cause a clear double burden on the health-environment synergy (Steenson & Buttriss, 2021). While the vegan and vegetarian diets are commonly analysed and proven to be beneficial for the environment, they are hardly realistic to introduce into high-income countries as the next step (Steenson & Buttriss, 2021). In a global, environmental footprint reduction targeted optimization study, Chaudhary & Krishna (2019) concluded that a higher intake of fruits, vegetables, pulses, and roots, similar to observed intake from cereals and lowered amount from meats, dairies, and eggs would serve the health-water footprint synergy in the region of Europe and Central Asia. This trend was true for Hungary as well, adding that fish food groups elevated slightly despite other meats. Another sustainable diet optimization study considering more environmental footprint (carbon, nitrogen, water, land) pointed out that in the optimized diets plant-based foods are common, while livestock rarely appears, which suggests a synergy between plant-based and seafood (Gephart et al., 2016). In a water footprint reduction targeting diet optimization study focused in India, Milner et al. (2017) found that wheat, dairies, and poultry lowered, while legumes increased in the optimized diets.

3.9.4. Main contributors to dietary water footprint to total diet among food groups

Studies concentrating on European countries and the total water footprint usually found meats followed by dairies as the main contributors, followed by cereals and vegetable oils (Capone et al., 2013; Sáez-Almendros et al., 2013; Vanham, Mekonnen & Hoekstra 2013) Gibin, Simonetto, Zanini & Gilioli (2022) conducted analyses on European countries and calculated meats and products followed by milk and dairies as the greatest dietary water footprint contributors. On the global level, for green water, meats, and cereals, considered separately, are the main contributors, along with plant-based foods (especially cereals, nuts, and sugars) for the blue water footprint. If the scenario is changed to a healthier one, plant-based foods take the place of the main contributors (Harris et al., 2020, Vanham, Mekonnen, & Hoekstra, 2020). In a global optimization study, Jalava et al. (2014) analysed baseline and stepwise-reduced animal-based food dietary scenarios and found that in the case of green water, the animal-based foods are the main contributors, while in the case of blue water, the cereals (Figure 8.). Lares-Michel et al. (2021) concluded in a Mexican population study identified protective and risk factors to exceed the dietary water footprint related to healthy diets. Red meats, beef, pork, lamb, and processed meats were significant ($p < 0.001$) pushing the risk by 93.92 times and other animal-based food groups (yogurt, cheese, and milk) increased the risk by 13.33 times, while natural and industrial juices by 4.64 times. Fish, fruits and vegetables, and non-fat cereals were identified as protective factors to surpassing dietary water footprint related to healthy diets. Steenson & Buttriss (2021) concluded that vegetables, fruits, especially nuts and non-alcoholic beverages have a great but under-estimated blue water footprint contribution that somehow explains why the trend in blue water differs from other footprints - including green water -: it only decreases slightly or even increases in the theoretical shift to more sustainable diets. In an Israeli population study ($n = 525$), Tepper et al. (2022) estimated that plant-based foods, especially fruits are the greatest contributors to the blue water footprint of individual diets. It should be noted that in Israel the proportion of blue water footprint falls into the range of 11.9-18.4 % (of total dietary water footprint) so it should be interpreted accordingly (Harris et al, 2020).

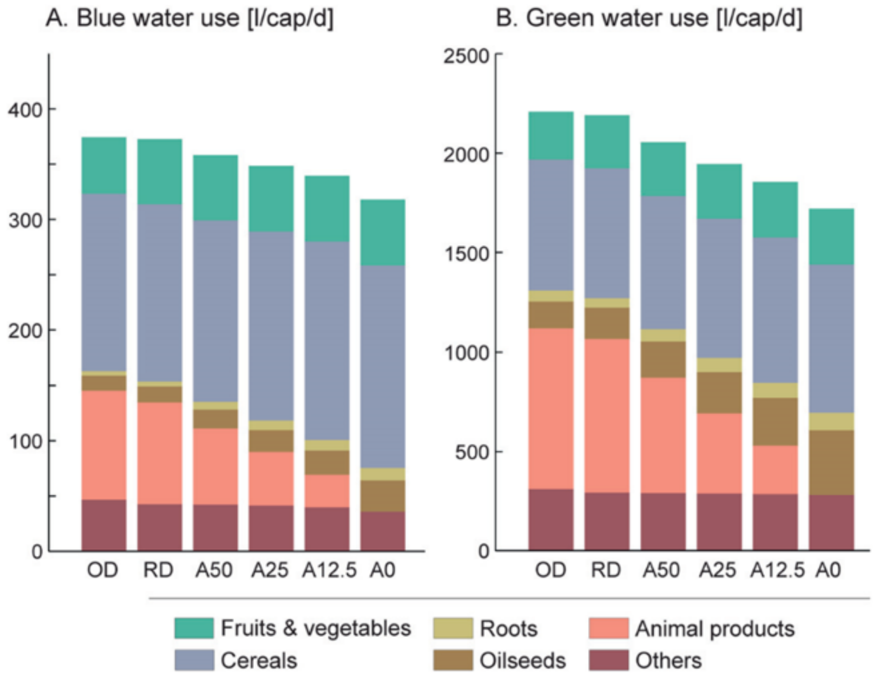


Figure 8:Contributon of the main food groups to the green and blue dietary water footprint (l/d/c) (Jalava et al., 2014), *OD: original diet, RD: recommended diet, A50: animal-based foods limited to 50% of original diet, A25: animal-based foods limited to 25% of the original diet, A12.5: animal-based foods limited to 12.5% of the original diet, A0: animal-based foods limited to 0% of the original diet,*

4. METHODS

4.1. Summary and logical relationship of the included studies

In the literature review section, the approaches and methods used in the international scientific scene of this field were described, and the specification of the Hungarian databases and application of methods will be described in this section. All analyses and optimization included three dimensions:

(1) socio-cultural dimension: cultural acceptability, sex

(2) ecological dimension: food-related or dietary water footprint,

(3) health dimension: dietary or nutritional quality.

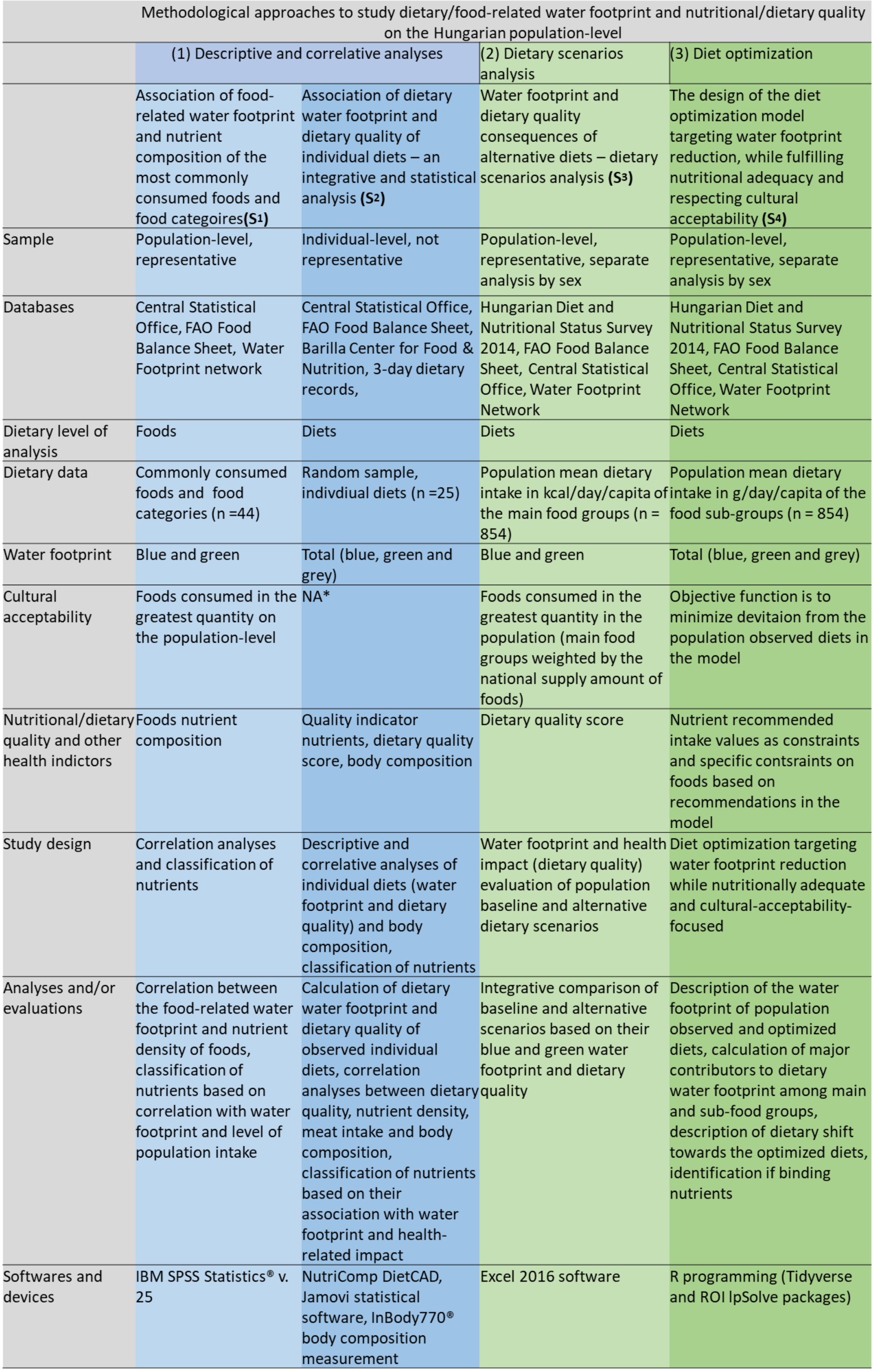
The studies constructing the dissertation are different in the means of dietary datatypes and data levels; they focused either on foods (S_1) or diets (S_2-S_4). In the case of the latter, two focus groups were analysed: a random sample representing the nutritionist's practical approach (S_2) and a population sample representing the population studies of sustainable nutrition (S_3, S_4) (Figure 9.).

S_1: Association of food-related water footprint and nutrient composition of the most commonly consumed foods and food categories (Tompa, Kiss, & Lakner, 2020)

S_2: Association of dietary water footprint and dietary quality of individual diets – an integrative and statistical analysis (Tompa, Kanalas, Kiss, Soós, & Lakner, 2021)

S_3: Water footprint and dietary quality consequences of alternative diets – dietary scenarios analysis (Tompa, Lakner, Oláh, Popp, & Kiss, 2020)

S_4: The design of the diet optimization model targeting water footprint reduction, while fulfilling nutritional adequacy and respecting cultural acceptability (Tompa et al., 2022).



	Methodological approaches to study dietary/food-related water footprint and nutritional/dietary quality on the Hungarian population-level			
	(1) Descriptive and correlative analyses		(2) Dietary scenarios analysis	(3) Diet optimization
	Association of food-related water footprint and nutrient composition of the most commonly consumed foods and food categoires**(S1)**	Association of dietary water footprint and dietary quality of individual diets – an integrative and statistical analysis **(S2)**	Water footprint and dietary quality consequences of alternative diets – dietary scenarios analysis **(S3)**	The design of the diet optimization model targeting water footprint reduction, while fulfilling nutritional adequacy and respecting cultural acceptability **(S4)**
Sample	Population-level, representative	Individual-level, not representative	Population-level, representative, separate analysis by sex	Population-level, representative, separate analysis by sex
Databases	Central Statistical Office, FAO Food Balance Sheet, Water Footprint network	Central Statistical Office, FAO Food Balance Sheet, Barilla Center for Food & Nutrition, 3-day dietary records,	Hungarian Diet and Nutritional Status Survey 2014, FAO Food Balance Sheet, Central Statistical Office, Water Footprint Network	Hungarian Diet and Nutritional Status Survey 2014, FAO Food Balance Sheet, Central Statistical Office, Water Footprint Network
Dietary level of analysis	Foods	Diets	Diets	Diets
Dietary data	Commonly consumed foods and food categories (n =44)	Random sample, indivdiual diets (n =25)	Population mean dietary intake in kcal/day/capita of the main food groups (n = 854)	Population mean dietary intake in g/day/capita of the food sub-groups (n = 854)
Water footprint	Blue and green	Total (blue, green and grey)	Blue and green	Total (blue, green and grey)
Cultural acceptability	Foods consumed in the greatest quantity on the population-level	NA*	Foods consumed in the greatest quantity in the population (main food groups weighted by the national supply amount of foods)	Objective function is to minimize devitaion from the population observed diets in the model
Nutritional/dietary quality and other health indictors	Foods nutrient composition	Quality indicator nutrients, dietary quality score, body composition	Dietary quality score	Nutrient recommended intake values as constraints and specific contsraints on foods based on recommendations in the model
Study design	Correlation analyses and classification of nutrients	Descriptive and correlative analyses of individual diets (water footprint and dietary quality) and body composition, classification of nutrients	Water footprint and health impact (dietary quality) evaluation of population baseline and alternative dietary scenarios	Diet optimization targeting water footprint reduction while nutritionally adequate and cultural-acceptability-focused
Analyses and/or evaluations	Correlation between the food-related water footprint and nutrient density of foods, classification of nutrients based on correlation with water footprint and level of population intake	Calculation of dietary water footprint and dietary quality of observed individual diets, correlation analyses between dietary quality, nutrient density, meat intake and body composition, classification of nutrients based on their association with water footprint and health-related impact	Integrative comparison of baseline and alternative scenarios based on their blue and green water footprint and dietary quality	Description of the water footprint of population observed and optimized diets, calculation of major contributors to dietary water footprint among main and sub-food groups, description of dietary shift towards the optimized diets, identification if binding nutrients
Softwares and devices	IBM SPSS Statistics® v. 25	NutriComp DietCAD, Jamovi statistical software, InBody770® body composition measurement	Excel 2016 software	R programming (Tidyverse and ROI lpSolve packages)

*NA: not applicable

Figure 9: Summary of methods based on specific aspects

4.2. Dietary and water footprint data that provided the base for the sustainable nutrition analyses focused on Hungary

Since the type and way of application of the dietary and water footprint data and databases were similarly used in all included studies, they will be first and once described to avoid repeating the same description, however, differences and specifications will be described in each case.

4.2.1. Hungarian Dietary and Nutritional Status Survey 2014

The Hungarian Dietary and Nutritional Status Survey (HDNSS) is a cross-sectional study conducted by the National Institute of Pharmacy and Nutrition (OGYÉI) in 2014, a more detailed description of the survey design is described elsewhere (Sarkadi Nagy et al., 2017). This study is representative of the Hungarian healthy and adult population and included a 3-day dietary record analysis from which the mean nutrient, energy, and food intake amounts were estimated for both sexes (n = 857), besides body composition data. There are several datatypes published or unpublished used in the studies of the dissertation:

(1) The energy and nutrient intake data and the Hungarian RDIs were applied as the basis for calculating DQSs, defining nutritional adequacy constraints in diet optimization, and the create a classification of nutrients based on their level of intake (S2, S3, and S4) (Sarkadi Nagy, Bakacs, Illés, Varga & Martos, 2016; Nagy et al., 2017, Rodler, 2005; Sarkadi Nagy et al., 2017; Schreiberné Molnár et al., 2017).

(2) The food group intake data in kcal/day/capita (published) was used as the basis for the baseline diet for the dietary scenario analyses (S3) (Sarkadi Nagy et al., 2017).

(3) The food intake data (g/day/capita) classified as "dietetic groups" (unpublished) was the basis for the estimation of observed diet (i.e. the reference point for cultural acceptability) in the diet optimization model (SM Table1). From these values, cultural acceptability constraints were also defined from the 10th and 90th population percentile of the food intake values (S_4) (SM Tables 2-5.).

4.2.2. Recommended Dietary intake Values

Besides the Hungarian recommendations (Rodler, 2005), RDI values published by other international organizations were applied in specific cases, when a value was missing or the study design required other solutions. These are the followings: (1) European Food Safety Authority (EFSA, 2017), (2) Food and Agriculture Organization of the U.S. and/or WHO (FAO and WHO, 2008; WHO, FAO and United Nation University [FAO, WHO and UNU], 2007).

4.2.3. Agricultural Organization of the United Nations (FAO): Food Balance Sheet

As described already in section 0., the FAO FBS (FAO, 2020). is a widely used food supply database in the field of sustainable nutrition (Hallström et al., 2015; Harris et al., 2020; Jones et al., 2016). The supply values are usually calculated with related conversion factors (FAO, 2000). Its national specific data was also applied in the studies of the dissertation for different purposes: (1) to estimate the food available in the greatest amount in the country, thus to use as the proxy of consumption, in these studies, preciously to relate weight to food items for the calculation of the weighted average of food groups (S_1, S_3), (2) to specify food groups in some cases such as the type of grains (S_4) based on the methods described by Gazan et al. (2018b)

4.2.4. Central Statistical Office of Hungary: food consumption data

The database of the Central Statistical Office (CSO) includes data of food consumption that is based on household surveys (n = 7485). These data are available for each year and classified by population percentiles based on socio-economic factors. Despite the dietary data being relatively detailed, it was not used to create the observed diet, since it does not represent a daily diet, but consumption of foods averaged in the population (g/capita/day). Thus, it was used for specification in all studies, for example, to define the different fruits in the "fruits and products" food group (S_3 and S_4), as well as to the estimated weight of different food items for the calculation of the weighted average of food groups in nutritional composition or water footprint values (S3) (Central Statistical Office of Hungary [CSO], 2018).

4.2.5. Nutrient composition data

Nutritional composition values were acquired from the Food and Nutrient Database for Dietary Studies (FNDDS) of the US Department of Agriculture (USDA) in the case of each study (S_1-S_4). This database is not Hungarian specific, which is a limitation for all analyses, but it is a widely accepted alternative for nutritional studies when there is no comprehensive and updated national database. The FNDDS database of the USDA is unified, thus containing energy and a wide range of nutrients for a great number of food items in the dimension of kcal, g, mg, or µg /100g food (United States Department of Agriculture [USDA], 2018). The nutrient composition is estimated at 100g o digestible part of foods.

4.2.6. Environmental impact data

For the estimation of dietary water footprint, the data is originated from the Water Footprint Network database, from which the Hungarian specific (country average) data was considered in l/kg of food and later transformed in some cases. In the case of the type of livestock water footprint, the values as the weighted average of different husbandry were considered (Mekonnen &

Hoekstra, 2010a, 2010b). In these studies, the green, blue (S1 and S3), and /or total water footprint (including the grey) were calculated (S_4). In the case of food items that are not produced in Hungary, the global average values were taken into the calculations. Since it's a widely used datatype, the characteristics are described in section 3.3.2.1. in more detail.

For the environmental impact calculation of S_2, different data was acquired from the Barilla Center for Food and Nutrition (BCFN). The environmental-healthiness double pyramid (described in section 3.3.2.1.) was published by this scientific organization (BCFN, 2016a; BCFN 2016b). Barilla's double pyramid was based on a robust environmental impact database that includes hundreds of published data and databases that are systemized and averaged at the level of food There are 3 environmental impacts categorized in their published materials: ecological, water, and carbon footprint (BCFN, 2016a, 2016b). This databased is also accepted to be used in sustainable nutrition analyses (Downs & Fanzo, 2015; Song, Li, Fullana-i-Palmer, Williamson, & Wang, 2017), however, it is not country-specific.

4.3. Scope and methods of the included studies

4.3.1. Association of food-related water footprint and nutrient composition of the most commonly consumed foods and food categories statistical analyses (S_1)

The scope of this study was to evaluate the correlation between nutrient composition and green and blue water footprint of the most commonly consumed food items and categories in Hungary and to classify nutrients based on their association with food-related blue and green water footprint and population intake level (Tompa, Kiss, & Lakner, 2020).

4.3.1.1. Dietary data, nutrient composition, and water footprint and their compilation

For the estimation of the most commonly consumed food items and categories, the FAO FBS dietary data was primarily used and specified by the database of CSO, especially to clarify the specific types of fruits and vegetables (CSO, 2018). In the case of both databases, the dataset of 2013 was considered. These units were transformed to g/day/capita and only food items and categories consumed in a reasonable amount (>4 g/day/capita) were included in the calculations. Finally, 44 food items and categories were listed (SM List 1.) that are the most consumed in Hungary and they were used as a basis for the further calculations. For the national specific green and blue water footprint estimation, the WFN's databases (Mekonnen & Hoekstra, 2010a, 2010b) were used and compiled with the dietary data and nutrient composition values of USDA FNDDS (USDA, 2018) following the methods of (Gazan et al. 2018b) described in section 3.4. Data compilation resulted in an input database for correlation analyses consisting of energy and nutrient composition (kcal, g, mg or μg /100g food) and green and blue water footprint (l / kg foods) of food items and categories consumed in the greatest amount in the Hungarian population.

4.3.1.2. Correlation analyses between nutrient density and green and blue water footprint of food items and categories

To test the correlation between the energy and nutrient density values (macronutrients, vitamins, and minerals), and the green and blue water footprint of food items and categories, Spearman’s rank correlation was selected instead of the Pearson correlation since not all of the assumptions of Pearson correlation were satisfied (e.g. normality and distribution), it was also proved by Kolmogorov-Smirnov test ($p < 0.05$). The significance level was adjusted to alpha=0.05 in each calculation. Calculations were performed with IBM SPSS Statistics® v. 25 (IBM Corporation, 2017).

4.3.1.3. Classification of nutrients based on their population intake levels and association with green and blue water footprint

Nutrients were classified based on their population intake level and correlation with food-related green and blue water footprint. The population intake level can be below, above, or resemble the RDI values. These levels were based on the published national average intake values from the HDNSS 2014 survey (Nagy et al., 2017; Sarkadi Nagy et al., 2017; Schreiberné Molnár et al., 2017). The food-related correlation with green and blue water footprint was non-significant, positive significant, or negative significant.

The datatypes and their logical relationship are represented in Figure 10.

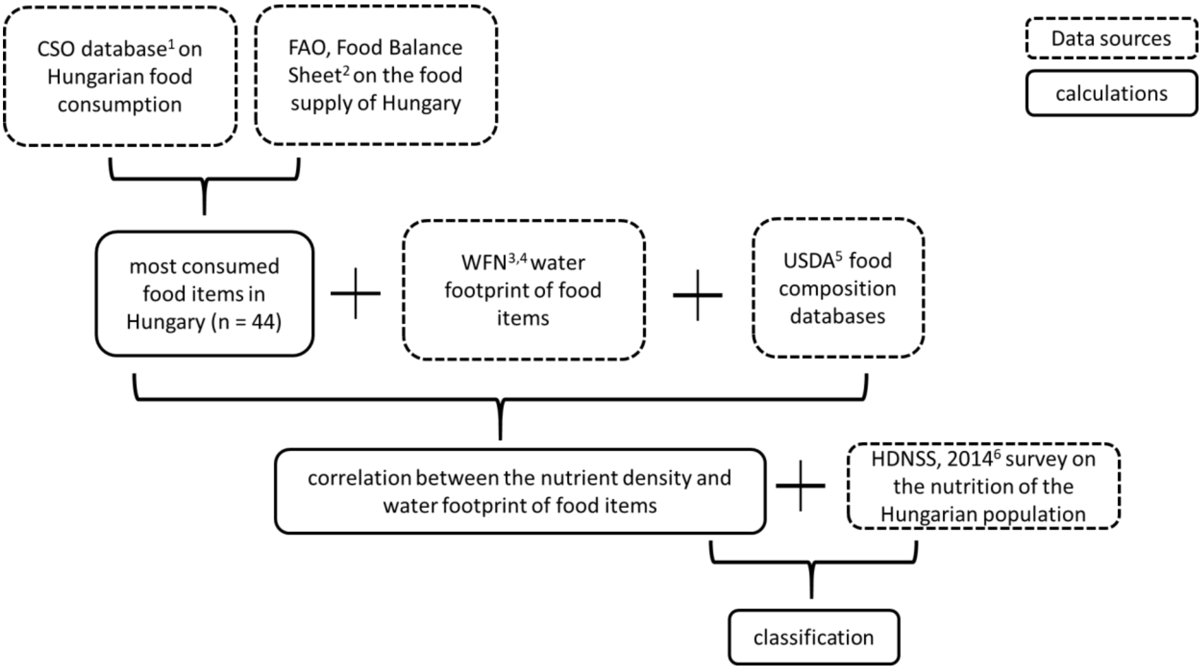


Figure 10: Logical figure of databases and compilation applied for the classification of nutrients based on blue and green water footprint and population intake level Tompa, Kiss, & Lakner, 2020), *1: Central Statistical Office of Hungary, 2: Food and Agriculture Organization of the United Nation, 3,4: Water Footprint Network, 5: U.S. Department of Agriculture, 6: Hungarian Diet and Nutritional Status Survey, 2014)*

4.3.2. Association of dietary water footprint and dietary quality of individual diets – integrative and statistical analyses (S_2)

The scope of this study was to apply a nutrition counselling practical approach to a random, non-representative sample of individuals. The study design included the usual measurement of nutritionist practice: diet analysis based on 3-day dietary records and body composition measurement with the addition of dietary water footprint analysis of diets. We aimed to identify the association between dietary quality, body composition – as health indicators – and the environmental impact of diets, besides, to identify sustainable dietary factors by using different analyses (Tompa et al.2021).

4.3.2.1. Characteristics of the sample

We recruited 30 healthy and adult (18+ years old) volunteers by an online questionnaire available from 08/05/2019 to 01/16/2020, individuals could agree to participate anonymously and by accepting (General Data Protection Regulation) GDPR consent. The sample consisted of 30 individuals: 23 women and 7 men. The characteristics of the sample were the followings: average age was 28 and they also self-reported their diet: 19 stated not to follow any particular diet, 7 kept plant-based and 4 followed a low-carbohydrate and high-fat (LCHF) diet. At the time of data collection, 11 individuals held college or university degrees while 14 had high school degrees, 24 of them lived in the capital or other cities, and 1 in a village. The number of samples varied among the analyses depending on which data could completely be acquired.

4.3.2.2. Dietary and water footprint data and their compilation

Dietary data was based on 3-days (2 weekdays and 1 weekend day) dietary records that were validated by dietitians and analysed by NutriComp DietCAD (Nutricomp étrend, 2014) software. As the results of the analyses, we could estimate the daily nutrient intake of individuals as well as the meat consumption summed or averaged for the 3 days. We also assessed the total meat intake as a sustainable dietary quality indicator, since the animal-based foods, especially meats predominantly are the greatest contributors to the environmental impact of diets (Chaudhary & Krishna, 2019; Gephart et al., 2016; Hallström et al., 2015; Harris et al., 2020; Steenson & Buttriss, 2021). Besides, according to the database of the Global Burden of Disease (GBD), the high amount of processed and red meat intake can be identified as individual dietary risk factors for the development of NCDs (IHM, 2019). Environmental data were acquired from the BFNC database for the double pyramid described in section 4.2.6 (BCFN, 2016a BFCN 2016b). For this study, water footprint was considered as the environmental impact category. Data compilation was made on a food category level, where the consumed food items reported by the individuals were matched with the environmental impact value of the proxy food category and multiplied by the intake amount. Food matching was carried out according to the method of Gazan, Barré et al. (2018) described in section 3.4.

4.3.2.3. Body composition measurement

We carried out a body composition with an InBody770® device that measures based on the bioimpedance of the body. It can distinguish lean and fat body mass because their electrical resistance is different. In this study, the "fitness score" was evaluated which is a score value measuring both lean muscle and fat body mass and independent of sex that was important due to the low sample number.

4.3.2.4. Dietary quality scores

A dietary quality score including both positive and negative dietary indicators was developed for the study. To categorize nutrients as qualifying (i.e. advantageous) or disqualifying (i.e. disadvantageous) related to health we based the classifications on the review of Hallström et al. (2018); these nutrients were considered as indicators for positive or negative dietary quality as applied by numerous international studies (Hallström et al., 2018; van Dooren et al., 2017). The RDI components of algorithms were based on the published recommendations of the HDNSS

(Nagy et al., 2017; Sarkadi Nagy et al., 2017; Schreiberné Molnár et al., 2017). The nutrients categorized as advantageous were the followings: total protein (g and energy intake share in %), dietary fibers (g), vitamin C (mg), calcium (mg), iron (mg), all in the dimension of day/capita intake. Protein as a nutrient that contributes to energy intake can be described by a range, so the algorithm results in optimal values between the minimum and maximum thresholds of the range and starts to decrease above and below it. The algorithm of protein (energy intake share in %) in the DQS (Equation 5.):

Equation 5.:

$$p(x) = \begin{cases} \dfrac{2x}{x_{ref_{min}} + x_{ref_{max}}} + 0.2 \ \ if \ \ x < x_{ref_{min}} \\ 1 \quad if \ \ x_{ref_{min}} \leq x \leq x_{\ ref_{max}} \\ \dfrac{-2x}{x_{ref_{min}} + x_{ref_{max}}} + 2.2 \ \ if \ \ x > x_{ref_{max}} \end{cases}$$

where: p is the sub-score referring to protein, x is the amount of protein in the diet, $x_{ref_{min}}$ minimum limit of the RDI range and $x_{ref_{max}}$ maximum limit of the RDI range. On the other hand, at the algorithm of advantageous nutrients, the score increases up to 150% of the RDI but not above, since the intake of excessive doses cannot be considered as advantageous and may cover the low intake of others. The algorithm of advantageous nutrients in the other DQS (Equation 6.):

Equation 6.:

$$N_{A(x)} = \begin{cases} \dfrac{x}{x_{ref}} \quad if \ \ x \leq 1.5 \times x_{ref} \\ 1.5 \quad if \ \ x > 1.5 \times x_{ref} \end{cases}$$

where: N_A is the sub-score refers to advantageous nutrients, x is the amount of advantageous nutrients in the diet, and x_{ref} RDI of the advantageous nutrient. The nutrients classified as disadvantageous were the followings: energy (kcal), sodium (mg), saturated fatty acids (g and energy intake share in %), and added sugars (g and energy intake share in %), all in the dimension of day/capita intake. In this case, estimation of the optimal value of energy intake was more sophisticated, since it was necessary to include the participants' physical activity level beside their individual parameters: gender, age, body weight, and height. We calculated the physical activity level coefficients based on the published paper by the EFSA (EFSA, 2017) for which we acquired the data from the online questionnaire filled out by the participants. The algorithm of disadvantageous nutrients in the DQS (Equation 7.):

Equation 7.:

$$N_{DA}(x) = 2 - \frac{x}{x_{ref}}$$

where: N_{DA} is the sub-score refers to disadvantageous nutrients, x is the amount of dis-advantageous nutrients in the diet, and x_{ref} RDI of the disadvantageous nutrient. The overall dietary quality score value was the sum of the sub-scores (Equation 8.). The algorithms were created in Excel 2016 software (Microsoft Corporation, 2018).

Equation 8.:

$$DQS = \sum_{t=1}^{n=4} N_{A_i} + \sum_{j=1}^{n=4} N_{DA_j} + p$$

where DQS is the dietary quality score, N_A is the sub-score is advantageous nutrients (i), N_{DA} is the sub-score of disadvantageous nutrients (j) and p is the sub-score of protein.

4.3.2.5. Correlation analyses and sustainable dietary factor identification

According to the aim of the study, the correlation between environmental impact, body composition, and dietary quality factors was carried out (Table 1.). Based on the type of scales and non-normal distribution of variables (Shapiro-Wilk test, $p < 0.05$) we chose to apply Spearman's rank correlation and determined the significance level at $p < 0.05$. We used Jamovi statistical analysis software for the correlation analyses (Jamovi, 2019; R core team, 2019). Our sample size ($n = 25$ or 30) was appropriate to determine the significance values of Spearman's rank correlation results according to an assessment of correlative statistical test (May & Looney, 2020), however, it was representative of any specific population. We carried correlation analysis among the following variables of sustainable nutrition:

Table 1.: Sustainable nutrition indicators as variables applied in the correlation analyses

Environmental impact indicators of diets	Health indicators
Water footprint (sum of green, blue, and grey water footprint) (l/d/c) **	Body composition (fitness score) Dietary quality scores Indicators nutrient intake (total energy (kcal/day), SFA*(g/d/c), added sugars (g/d/c), total protein (g/d/c), sodium (mg/d/c), iron (mg/d/c), calcium (mg/d/c), vitamin-C, dietary fibers (g/d/c) **

*SFA: saturated fatty acids

** g/d/c = gram/day/capita, mg/d/c =mg/day/capita, l/c/d = liter/day/capita

For the identification of sustainable diet indicators, we created a classification on the principles of the followings: (I.) Type of the nutrient: (1) advantageous in the aspect of health, (2) disadvantageous in the aspect of health (Hallström et al., 2018), and (II.) the type of correlation between the nutrient and WFP. (a) significant and positive, (b) significant and negative, (c) no significant correlation.

4.3.3. Water footprint and dietary quality consequences of alternative diets – dietary scenarios analysis (S$_3$)

The scope of this study was to evaluate the dietary quality (i.e. health) and dietary water footprint impact of different dietary scenarios based on the observed population diet and its alternative scenarios. In this comprehensive work, blue and green dietary water footprint assessment and two types of dietary quality scores (Sarkadi Nagy et al., 2016; EFSA, 2017; Rodler, 2005) and their integrative score was developed to assess the dietary quality of 6 different dietary scenarios; baseline, reduced meat, vegetarian, vegan, sustainable, cardio protective and ketogenic (Tompa, Lakner, et al., 2020).

4.3.3.1. Dietary and water footprint data and their compilation

For the creation of scenarios, the weighted average of nutrient composition and blue and green water footprint food groups were estimated based on the most commonly consumed food items and their supply amount acquired from the FAO FBS database and further specified with the help of the CSO database, for example, for the specification of “fruits other” (FAO, 2020). The food groups were the same as published in an HDNSS 2014 study (Sarkadi Nagy et al., 2017) in the dimension of kcal/day/capita intake of food groups specific for sexes that served as a baseline for alternative scenarios (The list of food and food groups are in SM Table 6.). For the estimation of the weighted average of the nutrient composition of the food groups, the most consumed food items were matched with their nutrient composition (nutrient density/100g) values from the USDA FDNSS database (USDA, 2018) according to the methods of Gazan, Barré et al. (2018) described in section 3.4. In this calculation, the supply amounts of foods were used as weights, and it was carried out according to the following formula (Equation 9.):

Equation 9.:

$$ND_p = \frac{\sum_{i=1}^{i=n} FI_{Si} FD_i}{\sum_{i=1}^{i=n} FI_{Si}}$$

where: ND_p is the weighted average of the nutrient density of the pth food group [nutrient quantity/100g], FI_s is the supply of i^{th} food item [100g/day/capita], FD_i is the nutrient density of food item [nutrient quantity/100g].

For the estimation of the weighted average of the blue and green water footprint of the food groups, a similar logic was used for compilation, the supply amounts were also applied as weight and water footprint data were acquired from the WFN database (Mekonnen & Hoekstra, 2010a, 2010b) (Equation 10.):

Equation 10.:

$$FG_{wf} = \frac{\sum_{i=1}^{i=n} FI_{Si} WD_i}{\sum_{i=1}^{i=n} FI_{Si}}$$

where: FG_{wf} is the weighted average of the water footprint of the pth food group [l/100g/day/cap], FI_s is the supply of food item [100g/day/cap], WD_i is the water footprint of food item [l/100g]. See Figures 11. and 12. Where the estimated values are presented.

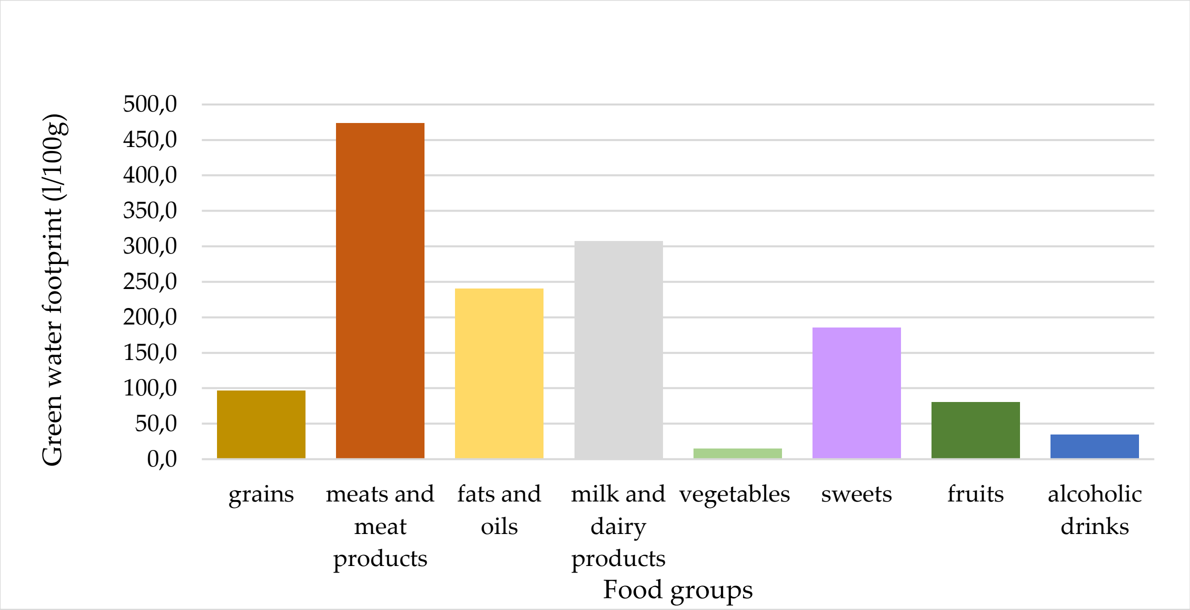


Figure 11.: Weighted average green water footprint of food groups (Tompa, Lakner, et al., 2020).

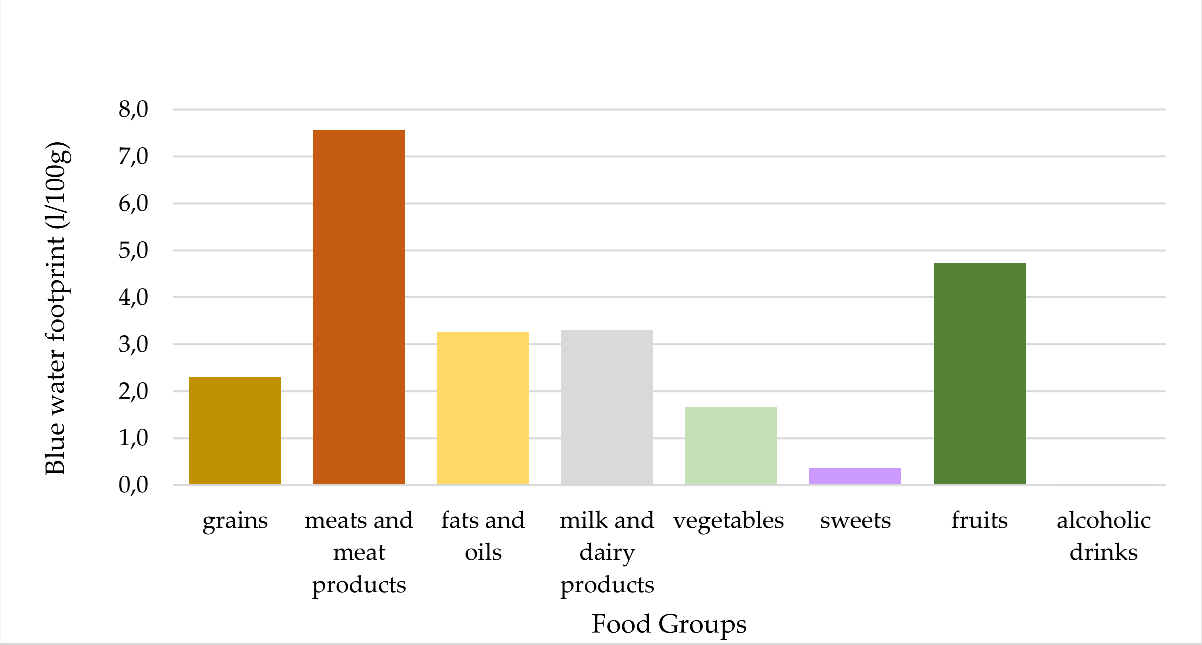


Figure 12.: Weighted average blue water footprint of food groups (Tompa, Lakner, et al., 2020).

The weighted average of food groups was used in the estimation of the dietary quality and dietary water footprint impact of the different scenarios in which the proportion of the food groups was different.

4.3.3.2. Dietary scenarios

The general methodology, application, and purpose of dietary scenarios are described in section 3.7., the specifications for this study are described in the followings. A set of food group intake quantities (practically: the food consumption structure) have been termed a scenario. The current observed average dietary pattern is termed the status quo or baseline scenario. The alternative scenarios are based on the baseline scenario; reduced meat content, and vegetarian, and vegan diet patterns were adopted to it. Besides, scenarios based on sustainable, ketogenic, and cardioprotective diets were also included. A sustainable diet was included in the analysis since it is a novel, environmentally conscientious approach to nutrition (Fischer & Garnett, 2016; Willett et al., 2019). A ketogenic diet was included because it is one of the most popular alternative diets; however, its high-environmental impact is rarely considered (Röös et al., 2015). A cardioprotective diet was also included since it is the most relevant in the case of public health in Hungary since cardiovascular diseases are responsible for the greatest proportion of mortality rates in developed countries, as well as in Hungary (IHM, 2019). A cardioprotective diet has already been analysed in terms of sustainability and showed promising results (Downs & Fanzo, 2015). The proportions of the different food groups in kcal in each scenario are visualized in Figures 13-14.

The characteristics of the different dietary scenarios are the following:

1. *Baseline (HDNSS-original):* The baseline scenario represents the current nutrition in Hungary; the proportions of food groups (kcal/capita/day) are based on the published data of the HDNSS (Sarkadi Nagy et al., 2017).
2. *Reduced meat content diet*: The reduced meat scenario is based on the baseline scenario; the meat food group was reduced by 50% in kcal and was replaced by eggs (12.5% in kcal), dairy products (12.5% in kcal), legumes (12.5% in kcal) and nuts (12.5% in kcal).
3. *Vegetarian diet*: The vegetarian scenario is based on the baseline scenario; the meat food group was reduced by 100% and was replaced by eggs (25% in kcal), dairy products (25% in kcal), legumes (25% in kcal) and nuts (25% in kcal).
4. *Vegan diet*: The vegan scenario is based on the baseline scenario; the meat and milk and dairy products food groups were reduced by 100% and replaced by grains (25% in kcal), potatoes (25% in kcal), legumes (25% in kcal) and nuts (25% in kcal).
5. *Planetary health diet (Sustainable)*: The sustainable scenario is based on the description of the planetary health diet. The planetary health diet is developed on the principle of respect for health and nature (Willett et al., 2019).
6. *Cardioprotective diet (Cardioprotective)*: The cardioprotective scenario is based on the elements of the cardioprotective diet (Mozaffarian, Appel, & Van Horn, 2011).
7. *Low-carbohydrate high-fat diet (Ketogenic)*: The ketogenic scenario is based on the widely accepted nutrient distribution of low-carbohydrate high-fat diets: 50-60% fat, 20-30% protein, and a maximum of 30% carbohydrates (Adam-Perrot, Clifton, & Brouns, 2006)

Common characteristics of the dietary scenarios:

1. All dietary scenarios are composed of food groups that include the weighted average of the most commonly consumed food items in Hungary in order to represent an assumed cultural acceptability of food items.
2. All dietary scenarios have a standardized energy content for both men (2718 kcal/day/capita) and women (2033 kcal/day/capita) that are based on the published data of the HDNSS (S4). Separation of male and female scenarios was necessary since the recommended nutrient values are sex-specific ones, and the published data of the HDNSS – which were the bases of all scenarios – are also specific for sexes (Sarkadi Nagy et al., 2017).
3. The food group of alcoholic drinks was included in all scenarios even if they were not included in all of the alternative dietary recommendations since they are present in the nutrition of the Hungarian population in a considerable amount (CSO, 2018) and the exclusion of them from alternative dietary scenarios would show biased results.

Based on the methodological principles described just above, the proportion of food groups (kcal/scenario) of the different scenarios separately presented for the two sexes was the following (Figures 13-14.)

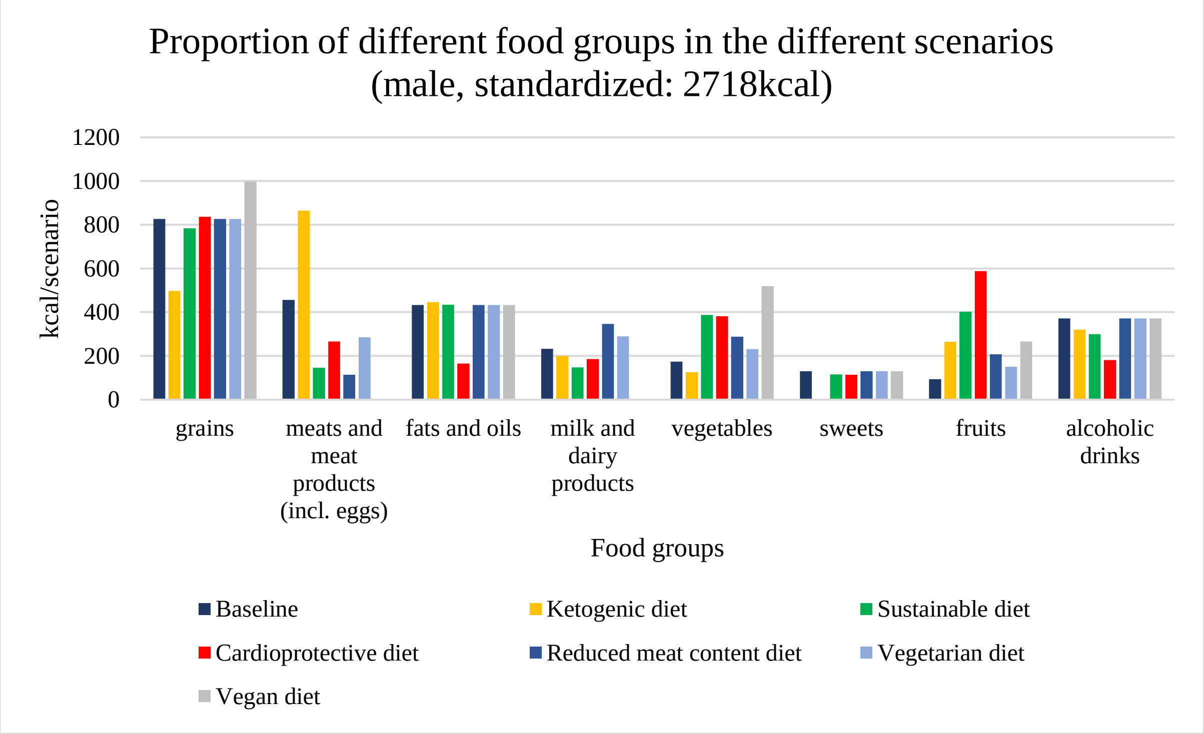


Figure 13.: Contribution of food groups in kcal/day/capita to the baseline and alternative dietary scenarios, men (Tompa, Lakner, et al., 2020)

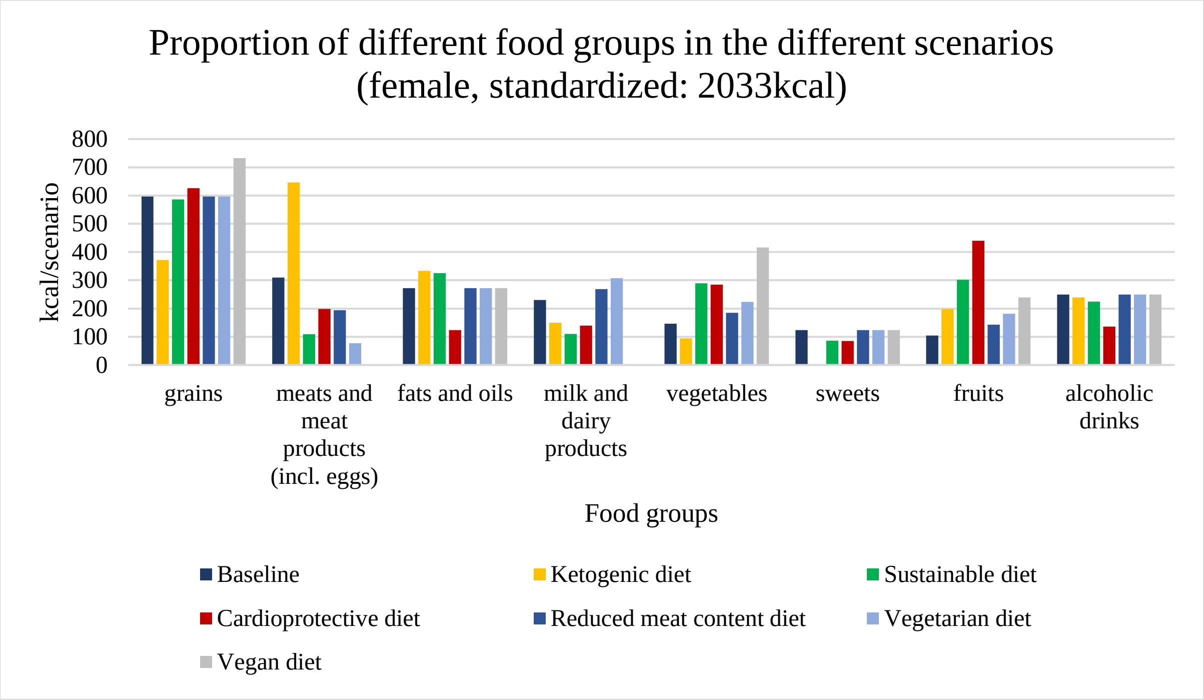


Figure 14.: Contribution of food groups in kcal/day/capita to the baseline and alternative dietary scenarios, women (Tompa, Lakner, et al., 2020)

4.3.3.3. Development and application of dietary quality scores

The general methodology, application, and purpose of DQSs are presented in section 3.5., the specifications of this study are described in the followings. The DQSs summed up the classified quantity of different nutrients in the scenarios, in that way they provided the evaluation of the dietary quality. Among several approaches to creating DQSs, in this study "the more is better" approach was used instead of indicators, meaning that not only a few important nutrients but as many as possible – based on available data and RDIs – were included in the calculations. Also, the basic algorithm principle of the scores was the ratio of RDIs and the actual level of nutrients in the scenarios as it is usually calculated (Hallström et al., 2018; Masset, Soler, Vieux, & Darmon, 2014; Masset et al., 2015; Masset, Vieux, et al., 2014; Perignon et al., 2016a). To ensure the comprehensive measurement of dietary quality, two types of DQSs were developed based on different recommendations from the Hungarian publications and EFSA report (EFSA, 2017; Nagy et al., 2017; Rodler, 2005; Sarkadi Nagy et al., 2016; Sarkadi Nagy et al., 2017; Schreiberné Molnár et al., 2017) and they were further processed into one integrative score. For the transformation of macronutrient RDIs into g/day/capita value, a reference human for both sexes was created, since these RDIs were in the dimension of % of energy share of kcal intake/day/capita and could have been applied in the study design. Based on Hungarian publications (Sarkadi Nagy et al., 2016) and an EFSA recommendation (EFSA, 2017) (SM Table 7.)

The nutrients included in the DQSs were divided into four main sub-domains, which resulted in four different sub-scores. These four sub-domains were the followings: (1) qualifying nutrients (2) disqualifying nutrients, (3) macronutrients with recommended intake range, and (4) recommended intake ratio of two nutrients. The classification was based on the intake level of nutrients and their association with health risks and protection described in section 3.5. in more detail.

(1) Qualifying nutrients: nutrients that are regarded as "positive" (Table 2.). The population's intake level of them is either adequate or low and a reasonably higher intake level is not related to health risks (EFSA, 2017; Nagy et al., 2017; Sarkadi Nagy et al., 2017; Schreiberné Molnár et al., 2017). In other words, diets that are rich in these nutrients are beneficial. In the case of qualifying nutrients, the scores increase positively with the nutrient density value up to 150% of the dietary reference value. At 150%, the scores will not increase further, so extreme nutritional density values will not be "rewarded" and cannot cover the low intake of others (Equation 11.). In the case of nutrients included in this group, toxicity should be considered only at an extreme intake value which is not realistic (EFSA, 2017).

Equation 11.:

$$N_Q = \begin{cases} \dfrac{N_s}{N_r} & if\ \ N_s \leq 1.5 \times N_r \\ 1.5 & if\ \ N_s > 1.5 \times N_r \end{cases}$$

Where: N_Q = Qualifying nutrient, N_s = Amount of the nutrient in the scenario, N_r = Recommended intake level of the nutrient

Table 2: Characteristics of the qualifying nutrients (Tompa, Lakner, et al., 2020)

Classification of nutrients	**Elements of Dietary Quality Score$_{HUN}$ (n = 16)**	**Elements of Dietary Quality Score$_{EFSA}$ (n = 14)**
(1) Qualifying nutrients (The population intake level of these is either adequate or low and a reasonably higher intake level is not related to health risks. To elevate their intake would be beneficial on the population level)	dietary fiber (g), thiamin (mg), riboflavin (mg), niacin (NE), vitamin B6 (mg), folate (µg), vitamin B12 (µg), vitamin C (mg), vitamin A (µg), vitamin E (mg), calcium (mg), magnesium (mg), zinc (mg), potassium (mg), iron (mg), phosphorus (mg)	dietary fiber (g), thiamin (mg), riboflavin (mg), niacin (NE), vitamin B6 (mg), folate (µg), vitamin C (mg), vitamin A (µg), calcium (mg), magnesium (mg), zinc (mg), potassium (mg), iron (mg), phosphorus (mg)

(2) Disqualifying nutrients: nutrients that are regarded as "negative" (Table 3.). The population's intake level of them is high and related to health risks (EFSA, 2017), Nagy et al., 2017; Sarkadi Nagy et al., 2017; Schreiberné Molnár et al., 2017). In other words, diets that are rich in these nutrients are unhealthy. Similar studies often include

disqualifying nutrients in their calculations (Darmon et al., 2009; Hallström et al., 2018; Masset, Solar, et al., 2014). In the case of nutrients included in this group, "less is more", so scores will decrease in correlation with the increase of the nutritional density values above the recommended maximum. In the case of nutritional density values that are under the maximum recommended intake, scores will increase in correlation with the increase of the nutritional density value. The score value for sugar is based on a relative comparison; the reference intake level is the calculated average intake of the population based on (Sarkadi Nagy et al., 2016). Even though there are recommendations for added sugar intake, calculations were mostly based on unprocessed food items, so instead of dietary reference values, the relative difference compared to the baseline scenario gave the score values for sugar (Equation 12.).

Equation 12.: $$N_{DQ} = 2 - \frac{N_S}{N_r}$$

Where: N_{DQ} = Disqualifying nutrient, N_s = Amount of the nutrient in the scenario, N_r = Recommended intake level of the nutrient

Table 3: Characteristics of the disqualifying nutrients (Tompa, Lakner, et al., 2020)

Classification of nutrients	**Elements of Dietary Quality Score$_{\mathbf{HUN}}$ (n = 5)**	**Elements of Dietary Quality Score$_{\mathbf{EFSA}}$ (n = 3)**
(2) Disqualifying nutrients (the population intake level of these is high and related to health risks). To lower their intake would be beneficial on the population-level.	sugars (g), cholesterol (mg), total fat (g), sodium (mg), saturated fatty acids (mg)	sugars (g), sodium (mg), saturated fatty acids (mg)

(3) Macronutrients with a recommended intake range: nutrients that contribute to energy intake (Table 4.). These usually have a dietary reference value that includes a relative range based on the total recommended energy intake or body weight. Total carbohydrates, total fat, and total protein are classified into these groups. Even though dietary fibers, sugars, cholesterol, and saturated fatty acids are categorized as types of macronutrients, they were classified in different subgroups since they have a differentiated role in human health (EFSA, 2017). Total fat was classified as a disqualifying nutrient in dietary quality score$_{\text{HUN}}$ since only a maximum dietary reference value was determined due to the high population intake level, and a lower intake would be beneficial (Sarkadi Nagy et al., 2016). However, in the summary report of the EFSA there is a recommended intake range, so in the case of dietary quality

score$_{\text{EFSA}}$ it is classified as a macronutrient with a recommended intake range (EFSA, 2017). To calculate the exact dietary reference values for macronutrients (as they are within the range of the recommended energy intake percentage) it was necessary to calculate as if for a reference human being, so for both dietary quality score$_{\text{HUN}}$ and dietary quality score$_{\text{EFSA}}$ a theoretical human of average age, weight, and physical activity level was considered (SM Table 7g). In the case of nutrients falling into this group, there is a recommended range, so it is problematic to classify them as qualifying or disqualifying. Scores will increase in correlation with nutritional density values up to the maximum level of the recommended range. If the nutritional density values exceed the maximum level of the recommended range, the scores will decrease in correlation with the increase above the maximum value (Equation 13.).

Equation 13.:

$$N_{range} = \begin{cases} \dfrac{N_s}{N_{range}} & if\ N_s \leq N_{rave} \\ 2 - \dfrac{N_s}{N_{rmax}} & if\ N_s > N_{rmax} \end{cases}$$

where: N_{range} = Nutrient with recommended intake range N_s = Amount of the nutrient in the scenario N_{rmax} = Maximum value of the recommended intake range of the nutrient, N_{rave} = Average value of the recommended intake range of the nutrient.

Table 4.: Characteristics of macronutrients with recommended intake range (Tompa, Lakner, et al., 2020)

Classification of nutrients	**Elements of Dietary Quality Score$_{\text{HUN}}$ (n = 2)**	**Elements of Dietary Quality Score$_{\text{EFSA}}$ (n = 3)**
(3) Macronutrients with recommended intake range (nutrients that contribute to energy intake and have a recommended reference range).	total carbohydrate (g), total protein (g),	total carbohydrate (g), total protein (g), total fat (g)

(4) Recommended intake ratio of two nutrients: nutrients that have an interaction with their absorption and/or utilization, the recommendation for their relative intake proportions, is based on the publications from the HDNSS 2014 study (Nagy et al., 2017; Sarkadi Nagy et al., 2017; Schreiberné Molnár et al., 2017) (Table 5.). In the case of these nutrients, scores will decrease if the ratio changes to favor disadvantageous nutrients

(Na and P) and will increase if the ratio changes to favor advantageous nutrients (K and Ca) (Equation 14.).

Equation 14.: $$N_{ratio} = \frac{(2-\frac{Na_S}{K_S})+(3-\frac{P_S}{Ca_S})}{2}$$

where: N_{ratio} = Recommended intake ratio of two nutrients, Na_S = Amount of Na in the scenario, K_S = Amount of K in the scenario, Ca_S = Amount of Ca in the scenario, P_S = Amount of P in the scenario.

Table 5.: Characteristics of nutrients with recommended intake ratio (Tompa, Lakner, et al., 2020)

Classification of nutrients	**Elements of Dietary Quality Score$_{HUN}$ (n = 2)**	**Elements of Dietary Quality Score$_{EFSA}$ (n = 0)**
(4) Recommended intake ratio of two nutrients (nutrients that interfere with each other in their absorption and/or utilization.	Na:K, Ca:P	

For the assessment, we created an integrated dietary quality value (IDQV). This has been calculated on basis of the DQS$_{EFSA}$ (Equation 15.) and the DQS$_{HUN}$ (Equation 16.). In the case of both scores the baseline scenario was considered as the reference point and all other scenarios were measured according to their deviation in % from it. The final value is the average deviation of dietary quality score$_{EFSA}$ and the dietary quality score$_{HUN}$ of the scenarios in % compared to the baseline. According to this calculation, the value of the integrated dietary quality value of the baseline scenario is 0. Those scenarios characterized by a “–" value are worse, and those by a "+" are better than the HNDSS-original scenario in the means of dietary quality. The algorithm for the IDQV is the following (Equation 17.):

Equation 15.: $$DQS_{EFSA} = \sum_{i=1}^{n=14} N_{D_i} + \sum_{j=1}^{n=3} N_{DQ_j} + \sum_{k=1}^{n=3} N_{range_k}$$

where DQS_{HUN} is the dietary quality score based on Hungarian published sources, N_D is the sub-score of qualifying nutrients (i), N_{DQ} is the sub-score for disqualifying nutrients (j), N_{range} is the sub-score for the nutrients with recommended intake range (k), N_{ratio} is the sub-score for nutrient with recommended intake ratio (l).

Equation 16.:

$$DQS_{EFSA} = \sum_{i=1}^{n=14} N_{D_i} + \sum_{j=1}^{n=3} DA_j + \sum_{k=1}^{n=3} N_{range_k}$$

where DQS_{EFSA} is the dietary quality score based on published sources by EFSA, N_D is the sub-score of qualifying nutrients (i), N_{DQ} is the sub-score for disqualifying nutrients (j), N_{range} is the sub-score for the nutrients with recommended intake range (k).

Equation 17.:

$$IDQV = \frac{\left(\frac{100 * DQS_{HUN} scenario_x}{DQS_{HUN} scenario_{baseline}}\right) - 100}{2} + \frac{\left(\frac{100 * DQS_{EFSA} scenario_x}{DQS_{EFSA} scenario_{baseline}}\right) - 100}{2}$$

where: $IDQV$ = Integrated dietary quality value, DQS_{HUN} = Dietary Quality Score, DQS_{EFSA} = Dietary Quality Score, $scenario_{baseline}$ = baseline scenario, $scenario_x$ = scenario

4.3.3.4. Analyses: an integrative approach

We evaluated the baseline and its alternative scenarios from an integrative aspect regarding blue and green dietary water footprint expressed in l/day/capita for each scenario and the dietary quality expressed as IDQV. We carried out all analyses separately for men and women.

4.3.4. The design of the diet optimization model targeting water footprint reduction, while fulfilling nutritional adequacy and respecting cultural acceptability (S_4)

The scope of this study was to create a diet optimization model targeting dietary water footprint reduction based on representative national dietary data. On the basis of linear programming, the model design aimed a stepwise reduction of dietary water footprint, while fulfilling nutritional adequacy and minimizing deviation from the population observed diet (Tompa et al., 2022).

4.3.4.1. Dietary and environmental data and their compilation

A more detailed description of datatypes are presented in section 4.2., so the specification for this study are described in the following summary.

The applied dietary intake data are a part of the non-published details of the HDNSS 2014 study, that were provided for this study by the Division of Nutritional Epidemiology, National Institute of Pharmacy and Nutrition that carried out the original survey. This dietary data is in the dimension of g/day/capita for food sub-groups (n = 35) that were also further classified into 11 main food groups specific for to sexes. Food sub-groups with > 4 g/day/capita intake were included in the calculations. Since this dietary data was on the individual level, the estimation of 10th and 90th population food intake percent for food sub-groups and main groups was possible that later appeared as a minimum and maximum cultural acceptability constraint in the diet optimization model. The population means intakes, 10th and 90th percentiles for food sub-group and main group intake are in (SM Tables 2-5). RDI values were applied as a minimum and maximum nutrient constraints in the model to ensure nutritional adequacy. The sources for RDIs were mostly from the original article of Vieux et al. (2018) using European recommendations (EFSA, 2017) and in specific cases, the WHO and/or FAO (FAO and WHO, 2008; WHO, FAO, and UNU, 2007), and Hungarian recommendations (Sarkadi Nagy et al., 2016; Rodler, 2005) were considered (SM Table 8.). For energy intake constraints the low to moderate physical activity factor and the median age of the population provided the proxy based on the publication of Sarkadi Nagy et al., (2016). For the nutrient composition of foods, the USDA FNDDS (USDA, 2018) database was applied with the addition of added sugar that was not included but traditionally important in Hungarian dietary recommendations (Sarkadi Nagy et al., 2016). The added sugar (g/100 g) content was estimated from the total sugar content (g/100 g) originated from the method by Louie et al. (2015), distinguishing four groups: (1) no sugars (added sugars = 0, e.g., animal fats), (2) no added sugars (added sugars = 0, e.g., legumes), (3) all sugars added (added sugars = total sugars, e.g., carbonated soft drinks), and (4) both natural and added sugars (added sugars = 50% of total sugars, e.g., jams). The dietary water footprint data was from the WFN database for both animal- and plant-based foods in kg/l (Mekonnen & Hoekstra, 2010a, 2010b). For this study, all types of water footprints (green, blue, and grey) were included in the total dietary water footprint values, and green and blue water footprints were applied separately as environmental constraints in the models and analysed in the results. After the further process and compilation of data, the water footprint values eventually were transformed into l/day/capita for the mean observed and optimized diets. For this analysis, the Hungarian national average values were acquired for livestock, the weighted average of grazing, and mixed and industrial husbandry. For the water footprint value of fishes, the estimation of Pahlow et al. (2015) was applied, since the WFN database does not contain values for fishes. Hungary can be described by a high agricultural production potential, that is why we assumed that the products that can be produced in Hungary were actually produced there. This hypothesis does not necessarily reflect the reality, because, due to cost differences, Hungary imports food products that could be locally produced (e.g., potatoes, apples). The global average of the dietary water footprint was matched for those food items that are not produced in Hungary (e.g., olive oil). Since foods and water footprint values were directly matched, the estimation of the dietary water footprint was based on the so-called “bottom-up” approach, in which the dietary water footprint is calculated by considering the national food consumption values multiplied by the specific water footprint values of food items. The compilation of foods with metrics (nutrient composition, dietary water footprint) was based on Gazan et al (2018a) work described in section 3.4. In some cases, when the further specification was needed to calculate the metrics for a food sub-group, other, Hungary-specific data sources were applied (e.g., data from the Central

Statistical Office of Hungary (CSO, 2018) for the weighted average of vegetables, the Food Balance Sheets of FAO (FAO, 2020) for the type of cereals, or the Hungarian School Catering Recipes Book for the recipe of baked pastries (Fehér Ferencné, Mák, Molnár, Tóth & Vékony (2020)).

4.3.4.2. Diet optimization model design

The diet optimization was population-based, meaning that the model was based on an average observed diet in g/day/capita (n = 1) (Gazan, Brouzes et al., 2018). The optimization was conducted separately for both sexes, and thus there were different sex-specific models. The model is originally based on Perignon et al. (2016a) study on optimization with linear programming, which was designed to reach nutritional adequacy and a stepwise reduction of GHGE and in parallel stay as close as possible to the observed population diet (i.e. culturally acceptable). Vieux et al. (2018) later adopted this methodology in European countries provided another predecessor for this study. Similarly, this model was designed to ensure nutritional adequacy and cultural acceptability by minimizing deviation from the observed diet and aimed at a stepwise reduction in the total dietary water footprint.

4.3.4.3. Parameters of the Model

Linear programming-based optimization model designs were created composed of the following input parameters: (1) decision variables (food sub-groups), (2) constraints defining the targets for the optimized diet, and (3) an objective function (to be minimized or maximized) that drives the dietary shift to reach the constraints (Gazan, Brouzes et al., 2018; van Dooren, 2018). The decision variables were the 35 food sub-groups with the sex-specific mean intake values from the dietary data of the HDNSS 2014 study (Sarkadi Nagy et al., 2017). Three different sets of constraints were applied that are commonly part of the diet optimization models constraints (Gazan, Brouzes et al., 2018; van Dooren, 2018): nutritional adequacy, cultural acceptability, and stepwise environmental impact reduction (SM Tables 2-6.). In this study, total dietary water footprint was the measured environmental impact category and different proportions of reduction were tested, while nutritional adequacy and cultural acceptability constraints were identical in all models. Two different objective functions were defined: the first one was set to minimize the total water footprint values (Equation 18.):

Equation 18.:

$$minimize\ f = \sum_{i=1}^{35} Q_i W_i$$

where *i* represents the 35 food sub-groups, Q is the quantity of food sub-groups (g/day/capita), and

W is the total water footprint (l/g) of food sub-groups. The second objective function was defined to minimize the relative deviation from the observed diets to fulfill the cultural acceptability aspect as much as possible (Equation 19.):

Equation 19.:

$$minimize\ f = \sum_{i=1}^{35} ABS\left(\frac{Q_{opt,i} - Q_{obs,i}}{Q_{obs,i}}\right)$$

where *i* represents the 35 food sub-groups, ABS refers to the absolute value, Q_{opt} is the optimized quantity of food sub-groups, and Q_{obs} is the mean observed quantity of food sub-groups.

Calculating the relative deviation from the observed value allowed us to consider the proportion of each food sub-group (%) instead of the absolute change (g). This decision was made by considering the weight change in different food sub-groups to be comparable (i.e. “relative”) and to benefit food sub-groups with a lower intake to keep the optimized diets more diverse in the number of food -subgroups. The explanation for it is that even small changes in a low amount of food sub-groups cost considerably in this model (compared to models operating based on the absolute weight change), thus these sub-food-groups were less likely excluded. Besides, this objective function favors a larger variation on fewer food items (Gazan, Brouzes et al., 2018), which is advantageous in this model, since there are several food sub-groups with low intake and 0 in the 10th percentile (i.e., the minimum limit).

4.3.4.4. Phases of Optimization and Models

In the 1st phase, the maximum feasible reduction (minimizing the water footprint as an objective function (Equation (1.) in the total dietary water footprint was estimated for both sexes (WFP_MIN models) to set target values for the stepwise reduction for phase 2. In the 2nd phase, the objective functions were set to minimize the relative deviation from the observed diets (Equation (2), starting with a model design with no reduction in the water footprint in which the maximum water footprint constraints were set as lower or equal to the observed values while fulfilling the recommended nutritional values, resulting in a healthier diet (WFP_OBS models). Step 1 reduction was approximately 50% of the maximum feasible reduction for both sexes, while step 2 reduction was defined as the maximum feasible reduction value (WFP-X% models). The 2 observed average diets and 3-3 optimized diets for the two sexes were designed to be nutritionally adequate (i.e. healthier diets) and culturally acceptable, assured by the constraints (details on the models are shown in Figure 15.).

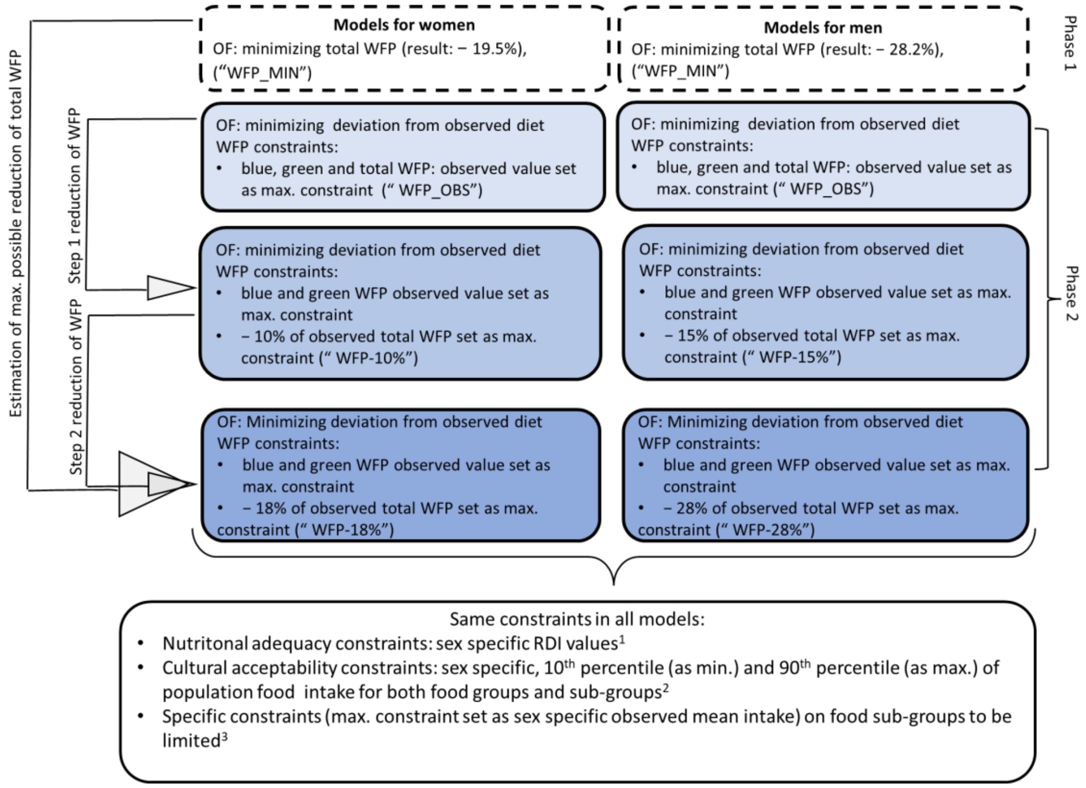


Figure 15: Schematic flowchart of the optimization phases, models, and parameters (Tompa et al., 2022)

[1] Recommended dietary intakes based on EFSA (EFSA, 2017), FAO and WHO (FAO and WHO, 2008), WHO (WHO, FAO, UNU, 2007), and the Hungarian recommendation (Rodler, 2005) (SM Table 8.)

[2] The 10th and 90th percentiles of population intake of food sub-group and group intake were estimated based on the representative population sample (men: n = 372, women: n = 485) from the HDNSS 2014 study (Sarkadi Nagy et al., 2017) (SM Tables 2-5.);

[3] Specific food sub-groups to be limited (max. constraint set as observed intake value) were based on country-specific aspects: (1) “wines” and “beers”: only energy and water footprint values were included in the calculation, since nutrient intake cannot be recommended from alcoholic drinks due to their “behavioral risk” status, contributing to the development of non-communicable diseases (European Commission [EC], 2022a; IHM, 2019), (2) recommended limitation on “offals and products”, (3) recommended limitation on foods with high added sugar content (“bakery products, pastries and sweets”, “sugar and honey”, and “carbonated soft drinks”)(Okostányér®, 2016) and (4)”meat products” due to the preference of leaner meats by the Hungarian Food-Based Dietary Guideline (FBDG) (Okostányér®, 2016), several European official guidelines and their status as an in-dividual dietary risk factor contributing to the development of non-communicable diseases (EC, 2022a; IHM, 2019; Okostányér®, 2016)

OF = objective function, WFP = water footprint, RDI = recommended intake value

4.3.4.5. Analyses of results

Population-based diet optimization is not suitable for statistical analyses, since there is only one average observed and optimized diet (Gazan, Brouzes et al., 2018). The total dietary water footprint of observed and optimized diets was calculated in relative (in %) and absolute water footprint change (l/day/capita) values for a comparison of the observed diets with the 3–3 sex-specific models in phase 2. The dietary shift for phase-2 optimization was the value of the objective function value (Equation (2)) that shows the difference between observed and optimized diets in the absolute sum of weight change of the food groups and food sub-groups (in %). Food groups' and sub-groups' contributions to the total dietary water footprint were presented with stacked column diagrams in absolute amounts (l/day/capita). The dietary shift between the observed and the optimized diet was described with data tables showing the positive or negative change in the amount of food sub-groups (g/day/capita), where the observed diet equals 0 g/day/capita as the baseline value (the observed intake values of main and sub-food groups are listed in the (SM Tables 2-5.). Finally, the "strength" of nutrient adequacy constraints was evaluated by indicating whether they reached the minimum and/or maximum value in the optimized diets. For data management and database compilation, the MS Excel software (Microsoft Corporation, 2018) and R programming (R core team, 2019). with Tidyverse package (Wickham et al., 2019) were used, and for optimization R programming with the ROI lpSolve package (Berkelaar, 2020) was used.

5. RESULTS AND DISCUSSION

The presentation of results and discussion follows the same logic as introduced in the methods section: the results of the four studies that form the dissertation will be described one by one (S_1-S_4) (Figure 9.)

5.1. Association of food-related water footprint and nutrient composition of food items – statistical analyses (S_1)

5.1.1. Correlation analyses between blue and green water footprint and energy and nutrient density

As Table 6 shows, Spearman rank correlation analyses between the variables (blue and green) food-related water footprint and nutrient composition of the most commonly consumed foods (n = 44) showed significant association in case of energy and each macronutrient (fibers, sugar, and carbohydrates positively, while total protein, cholesterol, total lipid, and saturated fatty acids negatively) with green water footprint and total protein, total lipid, cholesterol and saturated fatty acids (positively) with blue water footprint Among vitamins, riboflavin and B12 positively, while folic acid and vitamin-C negatively correlated with green water footprint. Regarding blue water footprint, only vitamin B-12 showed a positive correlation among vitamins. Among minerals, there was a significant correlation between nor green neither blue water footprints ($p < 0.05$).

Table 6.: Correlation analyses between blue and green water footprint and nutrient composition of the most commonly consumed food items in Hungary (n =44)

	Green water footprint (l/kg)		Blue water footprint (l/kg)	
	Correlation Coefficient	Significance	Correlation Coefficient	Significance
Energy (kcal)	0.715**	0.000	0.064	0.676
Macronutrients				
Total carbohydrates (g)	-0.311*	0.040	-0.206	0.178
Dietary fibers (g)	-0.367*	0.014	-0.112	0.466
Sugar (g)	-0.322*	0.033	-0.168	0.275
Total protein (g)	0.331*	0.028	0.387**	0.009
Cholesterol (mg)	0.570**	0.000	0.434**	0.003
Total fats(g)	0.756**	0.000	0.371*	0.013
Saturated fatty acids (g)	0.701**	0.000	0.317*	0.036
Vitamins				
Thiamin (mg)	-0.033	0.830	0.266	0.080
Riboflavin (mg)	0.322*	0.033	0.279	0.066
Niacin (NE)	0.0412	0.787	0.182	0.237
B6 (mg)	-0.056	0.719	0.218	0.155
Folic acid (μg)	-0.386**	0.010	0.174	0.258
B12 (μg)	0.574**	0.000	0.369*	0.014
C (mg)	-0.643**	0.000	0.157	0.307
A (μg)	-0.238	0.119	0.215	0.162
E (mg)	0.274	0.071	0.01	0.519
K (μg)	-0.164	0.286	-0.242	0.113
Minerals				
Calcium (mg)	-0.06	0.699	0.289	0.057
Magnesium (mg)	-0.007	0.965	0.205	0.183
Zinc (mg)	0.249	0.103	0.256	0.093
Phosphorus (mg)	0.221	0.149	0.249	0.103
Potassium (mg)	-0.152	0.332	0.041	0.792
Iron (mg)	-0.062	0.692	0.043	0.783
Sodium (mg)	0.045	0.781	0.121	0.455

**Correlation is significant at the 0.01 level (2-tailed), *Correlation is significant at the 0.05 level (2-tailed).

For correlation analyses, significant results were assumed, since GHGE as an indicator of environmental impact factors can predict correlation for other environmental impact categories such as green water footprint (van Dooren et al., 2017), however, it was found that the trend for blue water footprint is contradictory (Chaudhary & Krishna, 2019; Hess et al., 2015; Springmann et al., 2018; Steenson & Buttriss, 2021; Tom et al., 2016). In a Mexican population study, Lares-Michel et al. (2021) proved a strong, significant positive correlation between dietary water footprint (green and blue, l/day/capita) and energy intake (kcal/day/capita) based on daily dietary intakes. Besides, several studies have proved a relationship between nutrient density and GHGE of food items, and they were also used as comparisons to the results of this study. These studies have found a significant, positive correlation between the energy density of diets and GHGE (Hendrie, Ridoutt, Wiedmann, & Noakes, 2014; Vieux, Soler, Touazi, & Darmon, 2013) or energy density of food items and GHGE (Drewnowski et al., 2015; van Dooren et al., 2017). This study also found a strong, significant positive correlation between green water footprint with energy density but not with blue water footprint. Saarinen et al. (2017) have also calculated a significant correlation between folate (negative) and protein (positive) with GHGE, the same result was calculated for green water footprint, while in the case of blue water footprint, protein but not folate was calculated with significant positive correlation. In another similar study, a significant, positive correlation had also been proved between total protein and saturated fatty acids and GHGE (van Dooren et al., 2017), significant positive correlation was also found with green water footprint and SFAs. There was no significant correlation between any analysed minerals and green or blue water footprint, despite the findings of van Dooren et al. (2017) and Saarinen et al. (2017). The positive results of van Dooren et al. (2017) can be explained by the fact – except applying another environmental impact indicator - that they have analysed 403 food items, while in this study only 44 food items were analysed. However, Saarinen et al. (2017) have analysed only 29 food items and found a significant positive correlation between mineral density and GHGE.

According to our study and international results, the indicators nutrient for both environmental and healthiness dimensions could be energy and protein – well proved -, while saturated fatty acids and folate also can play a major role in the quality evaluation of sustainable foods and diets.

5.1.2. Nutrient classification is based on their association with blue and green water footprint and population intake

As Table 7. shows, regarding the classification of nutrients, group 1a (population intake is higher than recommended and positive significant association with food-related water footprint) consists of the clearest negative association with the two analyzed dimensions (water footprint and nutrient density), since energy and these nutrients (total lipid, saturated fatty acids, cholesterol, vitamin-B12) are associated with high food-related water footprint values and exceeded recommended intake on a population-level. Its inverse is group 3b (population intake is lower than recommended and significant negative correlation with food-related water footprint) which includes nutrients (total carbohydrates, dietary fibers, folic acid) that is associated with a low food-related water footprint and their population intake level is low. Group 1b (population intake is higher than recommended and negative significant association with food-related water footprint) with vitamin C and group 2a (population intake meets with recommendation and positive significant correlation with food-related water footprint) with total protein shows an ambiguous picture because their population intake and associated food-related water footprint show nor negative neither positive direction. Other analyzed nutrients did not show a significant association with water footprint so they were classified based on their population intake (1c, 2c, 3c). Despite its negative association with green water footprint, sugar could not be evaluated due to the recommendation that refers to added sugar, while there were natural sugars in the analysed food items in the majority. Vitamin-K was also excluded from classification because there were no data on its intake from HDNSS 2014 study.

Table 7.: Classification of nutrients based on correlation with the foods-related blue and green water footprint and population intake level based on the most commonly consumed foods and food categories

Type of nutrient	Type and direction of the correlation		
(1) The average intake of the Hungarian population is higher than the RDI	energy^{g}, total fats^{b,g}, SFA^{,g}, cholesterol^{b,g},vitamin-B$_{12}$^{b,g},	vitamin-C^{g}	niacin, vitamin-B$_{6,}$ vitamin-E (men), sodium, magnesium, phosphorus, iron (men)
(2) The average intake of the Hungarian population meets the RDI	total protein^{b,g,}		thiamin,
(3*)* The average intake of the Hungarian population is lower than the RDI	riboflavin^{g}	total carbohydrates^{g}, dietary fibers^{g}, folic acid^{g}	vitamin-A, vitamin-E (women), potassium, calcium, iron (women), zinc
	(a)significant (+) correlation with water footprint	(b)significant (–) correlation with water footprint	(c) no significant correlation

RDI: Recommended intake value

SFA: saturated fatty acids

b: blue water footprint

g: green water footprint

Based on the classification presented on Table 7., group 1a includes nutrients that are overconsumed and have a strong association with green and/or blue water footprint, in general, they are typically high in animal-based foods. Group 3b includes nutrients that are under-consumed and have weak association with GWP, in general, they are typically high in plant-based foods. Group 3b contains riboflavin, there was a significant positive correlation with green water footprint, and its intake does not reach the recommendation. However, the difference between the average intake (men: 1.46 and women: 1.24 mg day–1) and RDIs (men: 1.6 and women: 1.3 mg day–1) is not considerably great (Schreiberné Molnár et al., 2017). Riboflavin content is high in animal-based foods, but it is also found in pulses and grains in a considerable amount. Group 1b includes vitamin C which is somehow a controversial result, because nutrients that are typically high in vegetables and fruits and negatively correlate with green water footprint and have lower than optimal population intake, however, the average intake of vitamin C of the Hungarian population exceeds the RDI. In fact, fruits have a relatively high value of blue water footprint (Meier & Christen, 2012; Scheelbeek et al., 2020; Tompa, Lakner, et al., 2020) and they are on of the main sources of vitamin C but this analysis didn't show a positive correlation with blue water footprint with it. Group 2a includes protein, meaning that its intake meets with the RDI and has a high correlation to both blue and green water footprint. Since protein shows a strong correlation with dietary or food-related environmental impact (Saarinen et al., 2017; van Dooren et al., 2017) as well as usually classified as an advantageous nutrient (Hallström et al., 2018; Masset, Solar, et al., 2014; Masset et al., 2015; van Dooren et al., 2017), it could play a key role in the shift to more sustainable food consumption by optimization the quality and quantity of dietary proteins, especially considering the question the animal- and plant-based sources.

5.2. Integrative analyses of dietary records based on dietary water footprint and dietary quality – a practical approach (S_2)

5.2.1. Correlation analysis between the total dietary water footprint, dietary quality indicators, and fitness score

The correlation analyses between dietary water footprint and health indicators showed the following results: energy (r = 0.69, p = < 0.001), saturated fatty acids (r = 0.668, p < 0.001), protein (r = 0.747, p < 0.001, Figure 16D), and total meat intake (r = 0.734, p < 0.001, Figure 16A) had strong, positive significant correlation with dietary water footprint, while sodium (r = 0.477, p < 0.05) showed slight, positive but significant correlation with dietary water footprint. The dietary quality score (r = − 0.419, p < 0.05) was in a weaker, negative and significant correlation with dietary water footprint (Figure 16C). There were no significant results in case of fitness score and other indicator nutrients with dietary water footprint (p > 0.05). Besides, among dietary quality indicators, dietary quality scores and total meat intake (r = − 0.828, p < 0.001) showed a strong, positive and significant correlation (Figure 16B)

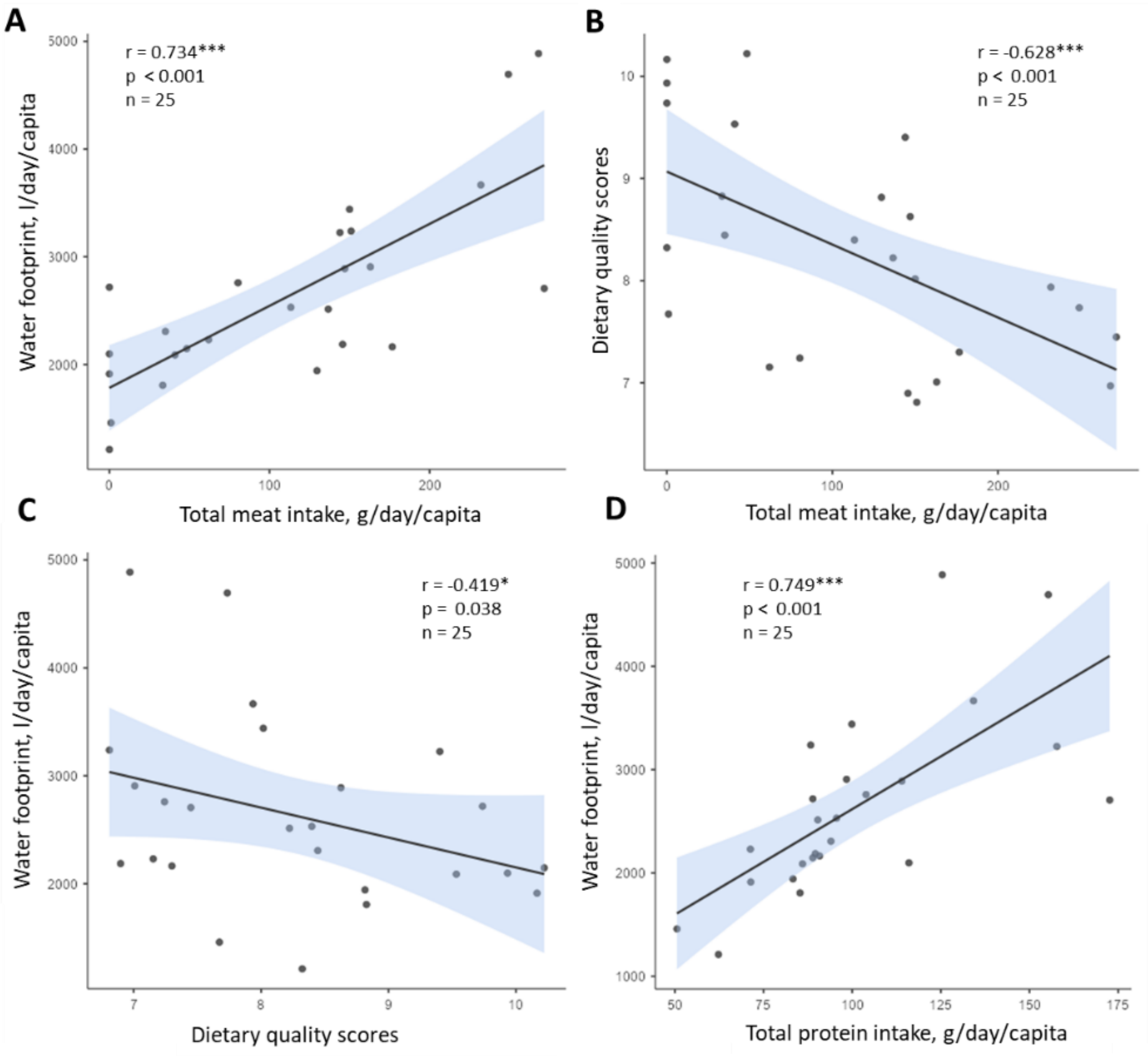


Figure 16: Correlation between dietary water footprint and dietary quality indicators (Tompa et al., 2021)

The mean total dietary water footprint volume of the analysed dietary records was 2629 l/day/capita (+/-879) which is somewhat different than the results (3635 l/day/capita) of the only analyses focused on this region of Europe calculated with total WFP values. (Vanham, Hoekstra & Bidoglio, 2013). This difference can be explained by the fact that Vanham, Hoekstra & Bidoglio (2013) estimated the nationally typical food intake based on the FAO FBS food supply data, while in this study, dietary records were analysed, an observation already pointed out by Vanham, Mekonnen & Hoekstra (2020). In the meta-analysis of Harris et al (2020), the average value of 3227 l/day/capita was estimated for Europe, however, this value was only for green and blue water combined, furthermore, in this study, grey water was also included in the total value. The explanation for the differences could be that the results of this study are not representative and included 6 plant-based diets that are typically lower in dietary water footprint. There was an inverse correlation between the DQS and dietary water footprint that suggests that the improvement of dietary quality would simultaneously decrease the dietary water footprint (16C). Also, dietary water footprint was a positive correlation with total meat intake which is not surprising regarding that meats have the greatest contribution to the total dietary WFP (Harris et al., 2020). Based on these results, it would be reasonable lowering the meat intake, while slightly increasing the intake of other animal- and dominantly the plant-based protein sources to keep up the adequate dietary protein intake. Furthermore, the DQS and total meat intake also showed an inverse correlation that suggests that diets higher in meat content could be lower in dietary quality.

5.2.2. Classification of nutrients based on their association with total dietary water footprint and advantageous or dis-advantageous health-related aspect

The classification in Table 8.,. lists no nutrients in 1a and 2a groups meaning that there was no negative significant correlation between dietary water footprint and nutrient intake values. Protein is classified in group 1b as the only advantageous nutrient in a positive correlation with dietary water footprint (also see Figure 16). In group 2b were the disadvantageous nutrients in positive correlation with WFP: energy (r = 0.690, p < 0.001), sodium (r = 0.477, p = 0.017), and saturated fatty acids (r = 0.668, p < 0.001). Group 1c includes dietary fibers, vitamin-C, calcium, and iron (mg/day), while 2c consists of added sugars from which non showed a significant correlation with dietary water footprint (p > 0.05).

Table 8.: Association of nutrients and water footprint of diets (n = 25). Spearman's rank correlation, significance levels: p < 0.001***, p < 0.01**, p < 0.05*(Tompa et al., 2021).

Type of nutrient	Type and direction of the correlation		
(1) Advantageous in the aspect of health	-	protein***	dietary fibers, iron vitamin C, calcium,
(2) Disadvantageous in the aspect of health	-	energy***, sodium*, saturated fatty acids***	added sugars
	(a)significant (-) correlation with water footprint	(b)significant (+) correlation with water footprint	(c)no significant correlation

The aim of the nutrient classification was to identify the integrative, environmental impact, and dietary quality indicator nutrients for this sample. According to our results, the disadvantageous nutrients were mainly identifiable as indicator nutrients based on their significant, positive association with total dietary water footprint (groups 2b: energy sodium, and saturated fatty acids) (Table 8.). Therefore, these nutrients could be regarded as negative indicators for the aspects of both dietary water footprint and dietary quality, and lowering the intake of foods high in them could be recommended. Lares-Michel et al. (2021) also calculated a strong, positive, and significant correlation between dietary water footprint and daily energy intake in a Mexican population study. Among other environmental pressures, the correlation between GHGE and energy density (Hendrie, Baird, Ridoutt, Hadjikakou, & Noakes, 2016; van Dooren et al., 2017), sodium (van Dooren et al., 2017) and saturated fatty acids (van Dooren et al., 2017) in diets has been described in other studies. Protein should be emphasized as an – sustainable diet – indicator nutrient, however, it shows a controversial direction: it has been shown a positive, significant correlation with GHGE in other studies (Saarinen et al., 2017; van Dooren et al., 2017) and with total dietary water footprint in this one. On the other hand, it has also been classified as advantageous in other studies (Hallström et al., 2018; Masset, Solar, et al., 2014) as well. In a previous (own) study the association between blue and green water footprint and protein content of the most commonly consumed food items in Hungary was already detected (S_1). The quality and origin of protein play a key role in sustainable nutrition; based on these results, the modification in the quality of dietary protein could also be recommended by decreasing the intake of meat-based protein while slightly increasing the intake of other animal- and dominantly plant-based protein source in proportion.

5.3. Green and blue water footprint and dietary quality impact analyses of baseline and alternative dietary scenarios (S_3)

5.3.1. Comparison of dietary scenarios in the dietary water footprint and dietary quality integrative approach

Dietary scenarios were analysed along two dimensions: dietary water footprint and dietary quality. The water footprint is measured in l/capita/day dimension and dietary quality is represented by the integrated value of the dietary quality score$_{\text{HUN}}$ and the dietary quality score$_{\text{EFSA}}$ (IDQV). There are four different analyses classified by sex and type of water footprint: (1) blue water footprint in female scenarios (Figure 17.) (2) blue water footprint in male scenarios (Figure 18.), (3) green water footprint in female scenarios (Figure 19.), (4) green water footprint in male scenarios (Figure 20.).

In the description, the rank of the scenarios refers to the most advantageous as 1st and the most disadvantageous as 7th in both dietary quality and water footprint.

(1) Blue water footprint in female scenarios.

Based on the integrative approach, regarding both the water footprint and dietary quality, the vegan (2nd in IDQV: +11.3 % and 1st in BWF: 20.4 l/capita/day) and the sustainable (3rd in IDQV: +9.7% and 2nd in BWF: 24.7 l/capita/day) scenarios were the most advantageous. The high vegetable and grain and no animal-based food content of the vegan scenario and the high vegetable, grains, and fruit content, besides the moderate milk and dairy product, meats, fat, and oil content of the sustainable scenario can explain these results. The cardioprotective scenario was 1st in IDQV (+16.7%) but 7th for its blue water footprint (43.4 l/capita/day), due to its high fruit content which contributes significantly to the total blue water footprint. The high fruit content also contributes to a high IDQV as fruits are typically high in qualifying nutrients and low in disqualifying nutrients (except for high added-sugar content in fruit products). The baseline scenario representing the current Hungarian nutrition pattern was the 7th in dietary quality value and 5th in blue water footprint (36.3 l/capita/day). Compared to the baseline scenario, the reduced meat, and vegetarian scenarios were lower in blue water footprint (4th and 3rd with 33.9 and 31.5 l/capita/day) and higher in IDQV (6th with +2.7% and 4th with +5.8%) but as much as expected, probably because only the meat group was modified and the scenarios were still low in vegetables and fruits and high in milk and dairy products. The ketogenic scenario was disadvantageous, being 6th in terms of its blue water footprint (40.2 l/capita/day) and 5th in dietary quality (+2.8%). This result of the ketogenic scenario was disadvantageous due to its high fat, oil, and meat content and low fruit and grain content (Figure 17.).

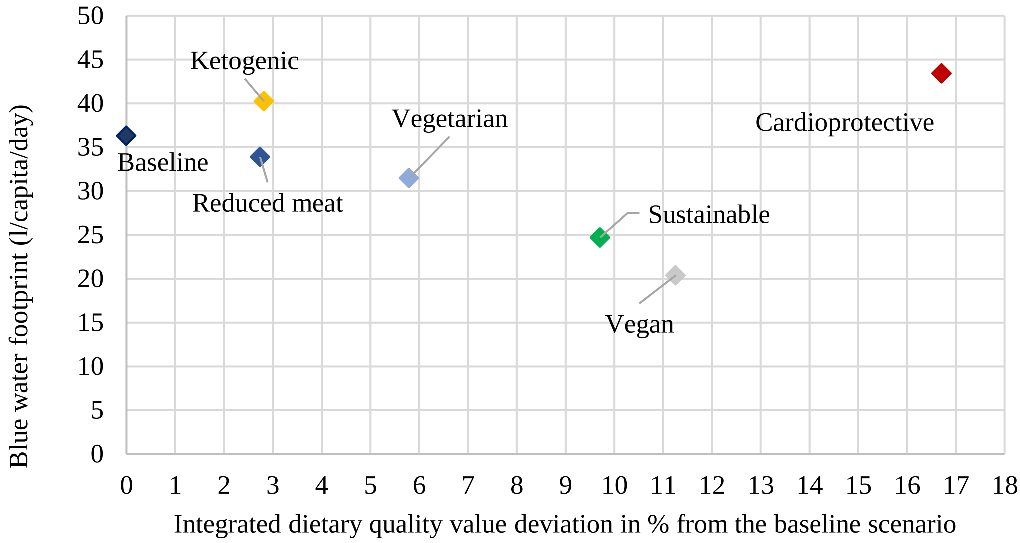


Figure 17.: Blue water footprint and dietary quality of the scenarios for women Tompa, Lakner, et al., 2020)

(2) Blue water footprint in male scenarios.

Somewhat similar to the female scenarios, the cardioprotective scenario was the 7th with its blue water footprint (58 l/capita/day) and the 1st in IDQV (+12.4%). These results occurred for the same reason as in the case of female scenarios: a high fruit content with relatively high grain and vegetable content. The sustainable scenario was the 2nd highest in IDQV (+9.1%) and 2nd lowest in blue water footprint (33.0 l/capita/day); hence it was the most favorable scenario in this analysis. This scenario is high in fruits, vegetables, and grains, while moderate in meats, milk and dairy products, and fats and oils. The vegan scenario showed less favorable results than it did in the female scenarios, ranking 3rd in IDQV (+4.1%); however, it was still 1st lowest in blue water footprint (24.5 l/capita/day). Compared to female scenarios, male scenarios are higher in energy and nutrient content, which can result in different rankings in IDQV. Baseline and reduced meat scenarios showed very similar results in both aspects (IDQV: 6th with 0.0% and 5th with +0.7%, BWF: 5th with 44.6 and 4th with 41.0 l/capita/day), probably because in the reduced meat scenario meats were partly replaced with animal based-foods that have similar characteristics in nutrient density and also has a high blue water footprint. The vegetarian scenario ranked 4th in IDQV (+3.0%) and 3rd in blue water footprint (37.5 l/capita/day). Similar to female scenarios, the reason that this scenario is not more advantageous is that only the meats group was modified and replaced by animal-based foods, nuts, and legumes, and it was still low in other vegetables and fruits. The ketogenic scenario was the most dis-advatanegous in both dimensions with a high blue water footprint and low dietary quality: 7th in IDQV: -7% and 7th BWF: 53.8 l/capita/day (Figure 18.)

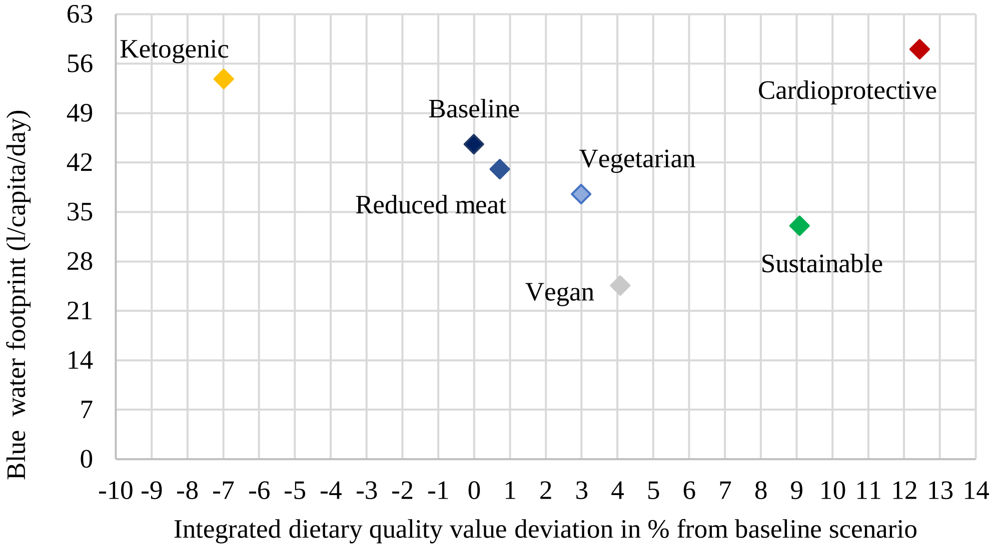


Figure 18.: Blue water footprint and dietary quality of the scenarios for men (Tompa, Lakner, et al., 2020)

(3) Green water footprint in female scenarios.

As explained earlier in section 3.9.2. blue and green water footprints in scenarios may show controversial results and this has also been proved in this present analysis. Besides its high dietary quality value (1st in IDQV: +16.7%), the cardioprotective scenario's green water footprint (GWF: 3rd with1724.4 l/capita/day) is also advantageous. The vegan (2nd in IDQV: +11.3%, 1st in GWF: 729.8 l/capita/day) and sustainable (3rd in IDQV: +9.7%, 2nd in GWF: 1257.9 l/capita/day) scenarios also showed promising results in this analysis. There were considerable differences between the baseline (7th in IDQV: 0.0%, 6th in GWF: 2238.7 l/capita/day), reduced meat (6th in IDQV: +2.7%, 5th in GWF: 2114.0 l/capita/day) and vegetarian (4th in IDQV: +5.7%, 4th in GWF: 1989.2 l/capita/day) scenarios in IDQV; however, there was only a slight difference in green water footprint. Baseline and ketogenic (5th in IDQV: +2.8%, 7th in GWF: 2538.0 l/capita/day) scenarios were the most disadvantageous scenarios overall, ranked as worsts in both aspects. In the case of green water, the animal-based food content clearly determined the rank of scenarios in terms of their overall water footprint. Dietary scenarios with a relatively high animal-based content also make a great contribution to a low IDQV since they are high in disqualifying nutrients such as saturated fatty acids, cholesterol, sodium, and total lipids (except for their high content of the qualifying protein content) (Figure 19.).

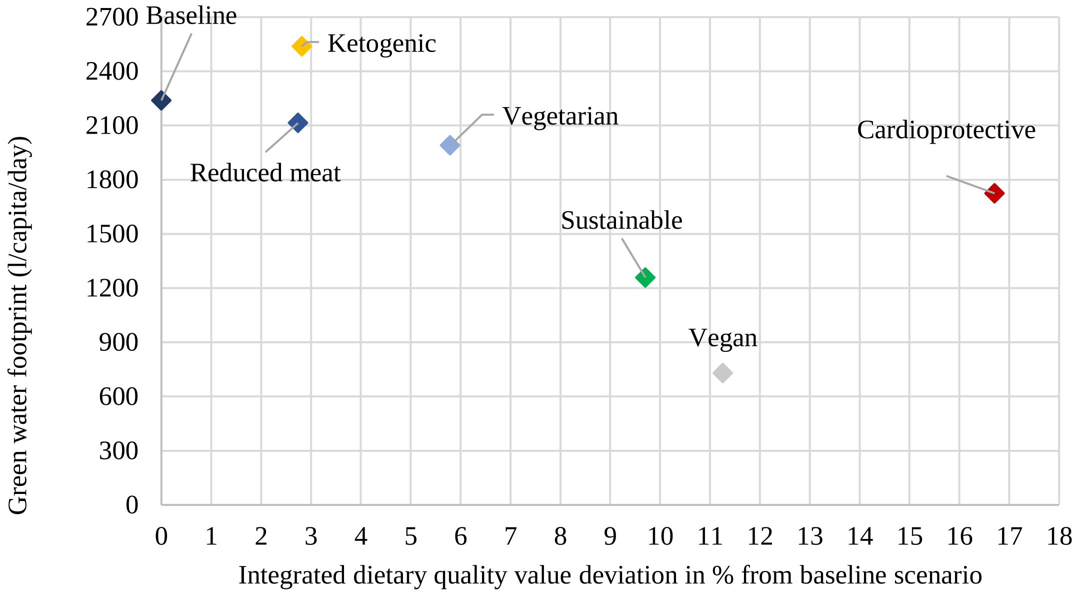


Figure 19.: Green water footprint and dietary quality of the scenarios for women (Tompa, Lakner, et al., 2020)

(4) Green water footprint in male scenarios.

Compared to the blue water footprint, the green water footprint of the cardioprotective scenario was more advantageous (3rd in GWF: 2305.4 l/capita/day, 1st in IDQV: +12.4%) which can be explained by the same reasons as in the case of the female scenarios. The most advantageous scenario was the sustainable one, ranked 2nd for both its green water footprint (1681.7 l/capita/day) and its dietary quality (IDQV: +9.1%); this can also be explained by the same reasons as the female scenarios. The vegan scenario was 3rd in dietary quality (IDQV: +4.1%) and 1st in green water footprint (954.7 l/capita/day). The baseline (6th in IDQV: 0.0% and 6th in GWF: 2785.6 l/capita/day), reduced meat (5th in IDQV: +0.7% and 5th in GWF: 2602.1 l/capita/day) and vegetarian (4th in IDQV: +3.0% and 4th in GWF: 2418.5 l/capita/day) scenarios were similar to the blue water footprint analyses of male scenarios because they were not considerably different, neither in their green water footprint nor in dietary quality. In this assessment, similar to the blue water footprint, the male, ketogenic scenario was described as most disadvantageous in both aspects (7th in IDQV: -7.0% and 7th in GWF: 3393.2 l/capita/day) (Figure 20.).

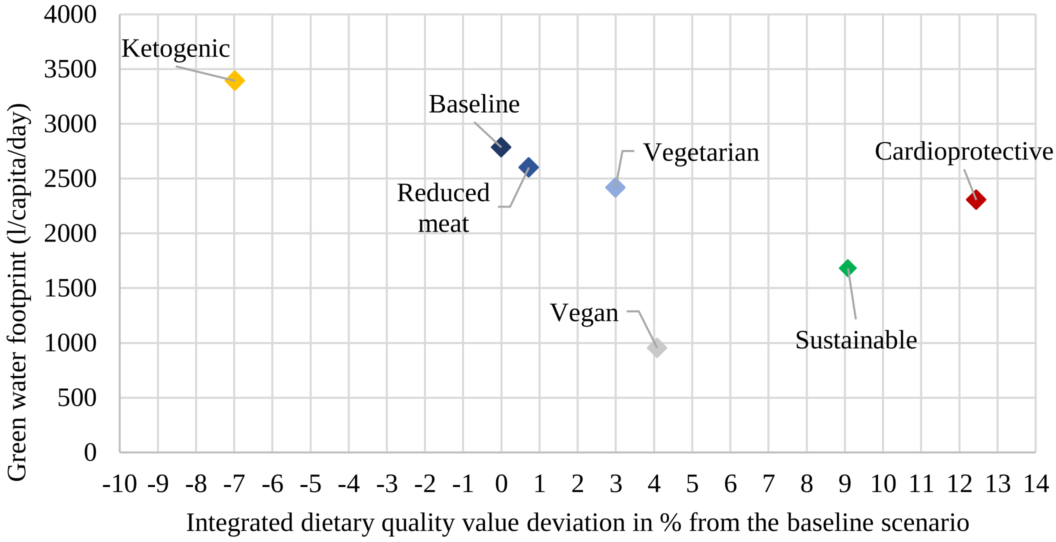


Figure 20.: Green water footprint and dietary quality of the scenarios for men (Tompa, Lakner, et al., 2020)

5.3.2. The synergy between dietary quality and environmental impact

The “healthiness" and environmental burden of a diet are two different dimensions, which is why, as a general rule we cannot deduce one from the other, except for meats and meat products: in the case of this product group, the pressure put on the environment by the production of them is considerably higher compared to other food groups. As stated, a clear stochastic relationship cannot be proven between sustainability and healthiness, but a reduction in the intake of animal-based foods would generally decrease the environmental burden of nutrition (Hallström et al., 2015; Harris et al., 2020; Jones et al., 2016; van Dooren et al., 2014; Vanham, Hoekstra & Bidoglio, 2013; Vieux et al., 2013). One of the main goals of the present study was to analyse synergies between the healthiness and water footprint of nutrition in the context of the typical Hungarian dietary pattern. Several similar studies have analysed this synergy, focusing on different populations using different metrics for environmental impact (Hallström et al., 2015, 2018; Harris et al., 2020; Jones et al., 2016; Springmann et al., 2018; Steenson & Buttriss, 2021; van Dooren et al., 2014). Given that this issue is enormously complex, with numerous contributory factors, the results are somewhat dependent on the sophisticated details. As already mentioned, the most often applied environmental impact factors (GHGE, land use, and water use except blue water footprint) are in correlation, so rough comparisons can be based on the results of other environmental impact categories. The most frequently applied factor is GHGE, which serves as an indicator of environmental impact (Dooren et al., 2017). According to the review on sustainable nutrition by Hallström, et al. (2015), the reduction in GHGE in vegetarian scenarios compared to current nutrition is about 20-35%, and in vegan scenarios 25-55%. Besides, in the case of total dietary water footprint, the change to no-animal food dietary scenario could result in a ~ 25% reduction, in the case of reduced-animal-based foods a ~ 18% decrease could be measured, while a shift to a healthier diet led to a slight, ~ 6% reduction (Harris et al., 2020). In this present study, considering both female and male, and green and blue water footprints the reduction of the water footprint in vegetarian scenarios was between 11.1-15.9%, and in vegan scenarios between 43.8-67.4%. This result is similar in the case of reduced meat scenarios (including vegetarian) but the present estimation on no-animal based scenarios showed a greater reduction that could be partly explained by the fact the share of blue water is among the lowest globally in Hungary, thus water footprint reductions are more dependent on green water that is in a clear correlation with animal-based food, while in case of blue water, the fruit content of scenarios varies the picture (Harris et al., 2020). Details on the absolute and relative blue and green water footprint reduction are in SM Table 9. The variation in the results is due to the different environmental impact categories and different methodology used to create and evaluate scenarios; however, there is no question that the less animal-based food features in the scenarios the more sustainable they are, but the "healthiness" aspect is quite limited since vegan diet poses a considerable risk for nutrient deficiencies and would way to big next step to be culturally acceptable (Nohr & Biesalski, 2007; Perignon et al., 2016a; Scarborough et al., 2012; Schüpbach, Wegmüller, Berguerand, Bui, & Herter-Aeberli, 2017; BDA, 2018; Vieux et al., 2020).

In this study, the most advantageous scenario was the sustainable one, based on the Planetary Healthy Diet published by Willett et al. (2019). This scenario contains a large amount of grains, vegetables and fruits and a moderate amount of meats, milk and dairy products, fats and oils, alcoholic drinks, and sweets. Vegan, vegetarian, and reduced meat scenarios were more advantageous than the scenario which represented the current Hungarian nutrition (baseline scenario). Other studies that analysed the sustainable nutrition of other populations in Europe have drawn similar conclusions (van Dooren et al., 2017; Vanham, 2013; Vanham, Hoekstra, & Bidoglio, 2013, Vanham, Mekonnen & Hoekstra, 2013). However, the situation is not as simple as claiming that the smaller the water footprint the healthier the nutrition, since any more detailed analyses of the water footprint (especially blue water footprint) show a more controversial picture (Chaudhary & Krishna, 2019; Hess et al., 2015; Jalava et al., 2014; Meier & Christen, 2012; Scheelbeek et al., 2020; Springmann et al., 2018; Tom et al., 2016; Vanham, Mekonnen & Hoekstra, 2013). This study also supported this fact and the separate analysis of green and blue water showed a somewhat controversial picture. The cardioprotective scenario also had the most synergetic characteristics: its green water footprint was lower and it was healthier than the current nutrition (baseline); however, in the case of the blue water footprint the opposite was true. The advantages of the cardioprotective diet in terms of sustainability have already been supported by Downs & Fanzo, 2015, however, they did not conduct detailed analyses separately on green and blue water footprints. The ketogenic (i.e.: a low-carbohydrate high-fat) diet is one of the most popular alternative diets nowadays; however, its high ecological impact is rarely analysed in the way it has been by Röös, et al. (2015); this present study also proved that the ketogenic diet is not a means of ensuring sustainable nutrition for the future. They concluded that the ketogenic diet has a higher environmental impact (climate impact, loss of biodiversity, land use) than current Swedish nutrition (+ 28%) and the Nordic recommended nutrition. In this present study, the increase in the water footprint was also considered in the ketogenic scenarios (female: GWF: +13.4%, BWF: +10.9% and male: GWF: +21.8% and BWF: +20.7%), although the assessed environmental impact category was different.

When drawing conclusions on the reduction in the water footprint in the different scenarios, green and blue water footprint was separated, as they were analysed separately in the present study. The results of the green water footprint will be compared to studies that have analysed either the green water footprint separately, or the total water use that involves both types of water (green and blue) and grey water included or not. It has been done, because green water footprint makes up the majority of total value in Hungary: 86-87% (Harris et al., 2020; Tompa et al., 2022). Besides, in terms of volume, total water use is similar to the green water footprint since it represents the largest proportion (Capone et al., 2013; Harris et al., 2020; Vanham, Mekonnen & Hoekstra, 2013). De Marco et al. (2014) calculated a negative association between a Mediterranean diet adequacy index and the water footprint, and Capone, et al. (2013) calculated a 69.9% reduction in the total water footprint in the case of a shift to a Mediterranean diet from the current Italian diet. In this study, the sustainable and cardioprotective scenarios most resembled the Mediterranean diet, and they also resulted in a considerable decrease in the green water footprint (female scenarios: -39,6% and -23,0%, male scenarios: - 43.8% and -17,2%) compared to the current Hungarian nutrition. In the case of reduced meat and plant-based diets, Vanham, Hoekstra & Bidoglio (2013) calculated a 27% reduction in the total water footprint in the Eastern-Central European region, including Hungary, while in this study the reduction in the green water footprint was -5.6-67.4 % in the female- and -13.2-65.7% in the male-related scenarios. In the case of the green water footprint and total water use, the amount of animal-based food has the greatest effect on the results (Harris et al., 2020; Vanham, 2013; Vanham, Hoekstra & Bidoglio, 2013; Vanham, Mekonnen & Hoekstra 2013). In the estimation of Harris et al. (2020), ~ -26% in case of no-animal-based food scenarios,

~ - 18% in case of reduced animal-based food scenarios, while e~ - 6% in case of healthier diets, that is almost the same results as in the total water footprint values.

Considering the results of the analysis of the blue water footprint and healthiness, the picture is more controversial and the stochastic relationship cannot exactly be proven; however, in terms of volume, the use of blue water is considerably lower compared to green water in Hungary. As has been described by Tom, et al. (2016), reducing meat intake could lower the environmental impact of nutrition; however, if we replace it with other high environmental impact food groups this effect can vanish. They carried out an analysis of the population of the United States and found that if they shifted from their current to the recommended nutrition the blue water footprint would increase by 10%. In the present study, the shift from current nutrition to sustainable nutrition would also result in a decrease in the blue water footprint (female scenario: -31.9%, male: -26.0%). However, proving the argument made by Tom, et al. (2016) in the case of cardioprotective scenarios, a partial replacement of meat with a high amount of fruit resulted in an elevated blue water footprint (female: +19.6%, male +30.1%). Hess et al. (2015) concluded that the shift in nutrition based on vegetarian and healthy scenarios in the UK population would only result in an insignificant change in the blue water footprint (-4-8%). Springman et al. (2018) also estimated an increase in the case of blue water footprint by the shift from the current diet to no animal-based food diets. Furthermore, in a review, Steenson & Buttriss (2021) also concluded that a shift towards more plant-based and less animal-based food diets could increase blue water footprint. In summary, regarding the blue water footprint, the picture is not as simple as to suggest that a reduction in animal-based food would directly lead to a lower blue water footprint, but a more complex change in nutrition could save blue water as was proven in this study in the case of the sustainable scenario.

5.3.3. Differences between the sexes

The differences between the two sexes in the analyses are mainly based on the fact that there were considerably different scenarios for them. Male scenarios were standardized to 2718 kcal while female scenarios to 2033 kcal, according to the published data of the HDNSS 2014 on daily energy intake (Sarkadi Nagy et al., 2017). The different ranking of scenarios in their health scores derives from the fact that the nutritional reference values were different for the two sexes (SM Table 7a-g.). In the case of scenarios where extreme upper and lower nutrient values were calculated (ketogenic and vegan), the results were proportionally more different due to the considerable impact of the initial energy density values. Also, there were greater differences in the water footprint of scenarios in the male compared to the female scenarios. Again, this derives from the simple fact that the energy density has a great effect on the size of the water footprint since the more we eat, the more water is used for food production. Daily energy intake and food energy density with dietary water footprint show a strong correlation (Lares-Michel et al., 2021; Tompa et al., 2021, Tompa, Kiss, & Lakner, 2020). In summary, regardless of the detailed analysis of green and blue water footprints and sexes, sustainable scenarios were the most advantageous. Meier and Christen (2012) analysed the difference between the sexes, although they applied a quite different approach. They concluded that the blue water use of food consumption was very similar for both genders, considering that in the case of other environmental impact factors (i.e. GHGE, land use, NH3 emission) this difference was greater between the two sexes. The reason for this lies in the structure of food consumption; while men consume more animal-based groups, women tend to consume more fruits, whose contribution to blue water use is considerable (Meier & Christen, 2012).

5.4. Sustainable diet optimization (S_4)

5.4.1. Dietary water footprint changes in healthy a culturally acceptable-focused diets

First, at phase-1 optimization (WFP_MIN models) (Figure 15.), the maximum possible total dietary water footprint reduction was 19.5% (557.0 l/day/capita) for women and 28.2% (1084.8 l/day/capita) for men, respectively. These values provided the target values for the stepwise optimization purposing water footprint reduction with minimizing relative deviation from observed diets as objectives. Since further changes in water footprint values were defined in each model (not to exceed those observed in WFP_OBS and the stepwise reduction in WFP-X% models), the total water footprint values changed in accordance of the model design. Table 9. shows that green water footprints, as the type of water that makes up the considerable majority (86–87%) of the total water footprint values, were simultaneously decreasing with them. Notably, in the case of step1 water footprint reduction for women (WFP-10%), blue water showed a greater decrease than at step 2 reduction (WFP-18%) despite the green and total values and the consistent decrease in the optimized diet for men. The proportion of the blue water footprint was consistently ~2% in each model for both sexes. The value of the “dietary shift” (relative change in weight) showed that the change towards a healthier diet (WFP_OBS models) required a greater diet change for women; furthermore, the step 2 reduction (WFP-18% and WFP-28%) caused a similar diet change for the two sexes (~31%), despite a 10% greater decrease in the water footprint for men.

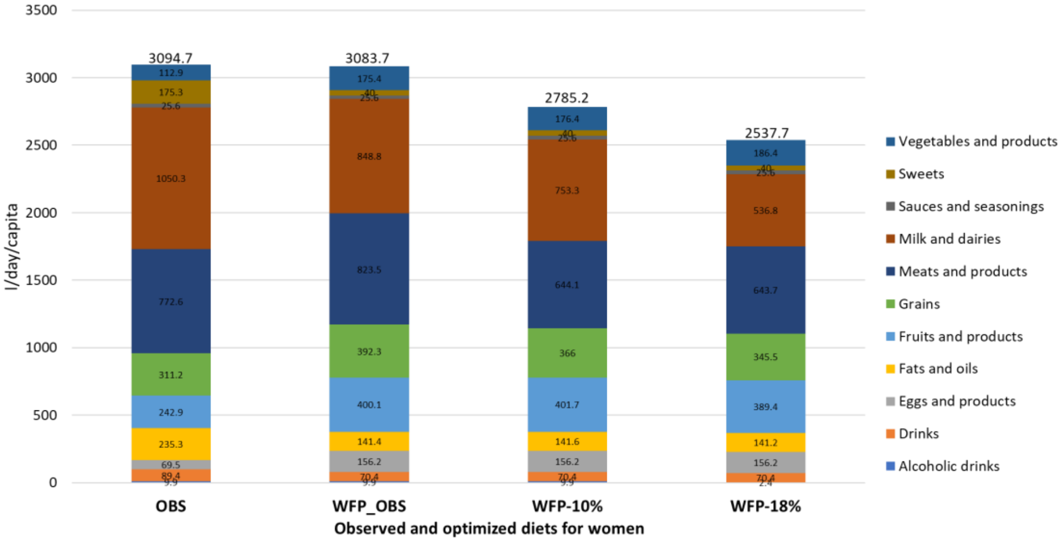
Table 9.: Change in the absolute and relative water footprint, the proportion of blue water footprint, and relative weight between the observed and optimized diets (Tompa et al., 2022)

	Blue WFP ^{1}	Green WFP ^{1}	Total WFP ^{1}	Relative Change in Total WFP ^{1}	The Proportion of Blue WFP ^{1} to Total WFP ^{1}	Relative Change in the Weight of Diet ^{2}
	l/Day/Capita			**%**		
Women						
Observed diet	62.0	2710.3	3094.7	baseline	2.0	baseline
WFP_OBS	54.5	2710.3	3083.7	−0.4	1.8	23.1
WFP-10%	52.5	2427.4	2785.2	−10.0	1.9	25.4
WFP-18%	54.3	2195.2	2537.7	−18.0	2.1	31.9
Men						
Observed diet	78.4	3367.7	3874.2	baseline	2.0	baseline
WFP_OBS	68.3	3367.7	3864.6	−0.2	1.8	18.0
WFP-15%	65.8	2861.7	3293.1	−15.0	2.0	21.6
WFP-28%	55.6	2404.1	2789.4	−28.0	2.0	31.5

There is no clear agreement on the association between healthiness and the environmental impact of diets in general (Downs & Fanzo, 2015; Gazan, Brouzes et al., 2018; Jones et al., 2016; MacDiarmid, 2013; Perignon et al., 2017; Tom et al., 2016; Vieux et al., 2013), but the synergy between a healthier diet and a lower dietary footprint does exist. This has also proven true for the dietary water footprint by this and numerous other studies analysing the shift between the observed and healthier diets (Capone et al., 2013; Harris et al., 2020; Jalava et al., 2014; Lares-Michel et al., 2021; Milner et al., 2017; Sáez-Almendros et al., 2013; Tom et al., 2016; Tompa, Lakner, et al., 2020; Vanham, Hoekstra & Bidoglio, 2013; Vanham, Mekonnen & Hoekstra 2013). However, this association is neither linear nor general, which is also well presented in this study. Based on our results, the blue water footprint of the WFP_OBS models – optimized to be nutritionally adequate – showed a considerable decrease (~12%), but not the green or total water footprint values (the increase was not feasible due to the maximum constraints) in the models. On the other hand, it was possible to reduce the dietary water footprint by 19.5% (for women) and 28.2% (for men) and still fulfill the dietary recommendations. This contradiction is also supported by other studies where a shift to a healthier and more sustainable diet resulted in only a small drop or increase in the blue water footprint (unlike other food-related footprints (Chaudhary & Krishna, 2019; Hess et al., 2015; Springmann et al., 2018; Tom et al., 2016) but these studies did not evaluate the total or green water footprint that is recently suggested and applied (Falkenmark & Rockström, 2006; Harris et al., 2020; Hoekstra, 2015, 2017; Vanham, 2020). Consequently, as this study also showed, when the total water footprint with all elements is included there should be put a special consideration for each element (Ansorge & Stejskalová, 2022). When adding the third focused aspect, cultural acceptability, these results also show that it is possible to reach a great reduction in the water footprint and ensure nutritional adequacy while respecting the adherence to the observed dietary patterns. This fact strengthens the idea that sustainable diet optimization should include cultural acceptability (Gazan, Brouzes et al., 2018; Meier & Christen, 2012; Perignon et al., 2016a; van Dooren, 2018) since the environmental burden can be eased when controlling this aspect as well. Chaudhary and Krishna (2019) optimized diets to lower different food-related footprints resulting in an increase in the blue water footprint (unlike other footprints) by 12% while causing a 45% dietary shift for Hungary (Chaudhary & Krishna, 2019). On the contrary, this study resulted in a blue water footprint change of −12.4% for women and −24% for men, with a ~32% dietary shift at the step 2 water footprint reduction. Vanham, Hoekstra & Bidoglio (2013) estimated a −11% reduction in the total water footprint by shifting to a healthy diet scenario (and −27% shift to a vegetarian diet) for the Eastern region of Europe, which seems to be a somewhat similar result to the 23.9% (both sexes) total water footprint decrease in this study, adding that no main food group (e.g., meats) was eliminated. A study focusing on Hungary, but applying different databases and scenario analyses, estimated the "sustainable scenario" as the most advantageous in the green and blue water footprint and health synergy, with −42% in green water and −29% in blue water change, and the ketogenic scenario as the most disadvantageous, with +16% in green water and +18% in blue water change for both sexes with considerable dietary shifts (Tompa, Lakner, et al., 2020). Harris et al. [18] estimated in a global-scale meta-analysis that the studies could reach up to a 25.2% total, 26.1% green, and 11.6% blue water footprint reduction with no animal-based foods, ~ 18% drop in green, blue ant total water footprint in case of reduced animal-based products, and around a ~6% total, green, and blue water change with the shift to healthier diets (Harris et al., 2020). Similarly, this model could create the smallest reduction in the blue water footprint (19.1%) compared to the green (24.7%) and total (23.8%) water footprint as the mean of both sexes, although designing only healthy diets and eliminating the main animal-based food groups nor completely neither partly. Instead, it resulted in a change of the quality of meat and meat products and milk and dairies. Jalava et al. (2014), using quadratic programming, could reach a reduction from −100 to 0 l/day/capita in blue water and from −1000 to −500 l/day/capita in green water by shifting from the original diet to a healthier diet for Hungarian consumers by minimizing the deviation from the observed diets (Jalava et al., 2014). While averaging the two sexes, there was a change of −15.3 l/day/capita in blue water and −739.3 l/day/capita in green water in the present model, which lies in the estimated range. The proportion of the dietary blue water footprint, compared to the total water footprint value, was ~2% in each model for both sexes, resembling the estimated range (2.3–7%) from the meta-analysis of Harris et al. (2020). The differences pointed out in the mentioned studies could be partly originated in the profound methodological differences (e.g., scenario analyses vs. diet optimization), however, they support the conclusion (Hallström et al., 2015; Springmann et al., 2018) that a context-specific approach could be more efficient in finding the existing healthiness-environment synergy.

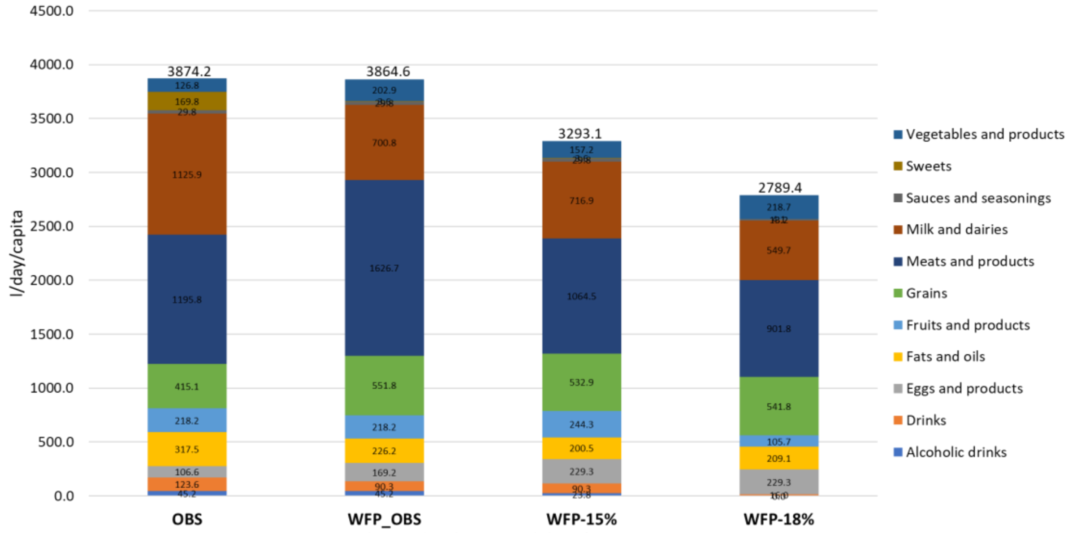
5.4.2. Dietary water footprint contribution of food groups and sub-groups to total dietary water footprint

The analyses on the total water footprint contribution of the main food groups in the observed diet showed that in the case of women the ‘milk and diaries’ group (1050.3 l/day/capita; 33.9%) followed by the ‘meats and products’ group (772.6 l/day/capita; 25.0%), while in the case of men the ‘meats and products’ group (1195.8 l/day/capita; 30.9%) closely followed by the ‘milk and diaries’ group (1125.9 l/day/capita; 29.0%) were the major contributors to the total dietary footprint. In the optimized models with the step 2 reduction of the water footprint (WFP-18%, WFP-28%) for both sexes, the contribution of ‘milk and dairies’ decreased considerably decreased (−576.2 l/day/capita for women and −513.5 l/day/capita for men), while ‘meats and products’ decreased moderately (−128.9 l/day/capita for women and −294.0 l/day/capita for men). Thus, meats and products were the major contributors to the total water footprint, with 25.4% for women and 32.3% for men, respectively. Another notable change in the main food groups to the dietary water footprint contribution was an increase in ‘fruits and products’ (+146.5 l/day/capita) for women and ‘grains’ (+126.7 l/day/capita) for men in the step 2 reduction models, compared to the observed diets, which made them the 3rd greatest dietary water footprint contributor. In the ‘sweets’ food groups, a considerable water footprint contribution drop was observed for both sexes: −135.3 l/day/capita for women and −165.7 l/day/capita for men (Figures 21 and 22).



OBS = observed diet, WFP_OBS = optimized diet with no water footprint reduction, WFP-10%= optimized diet with 10% water footprint reduction, WFP-18% = optimized diet with 18% water footprint reduction

Figure 21.: Contribution of the main food groups (n = 11) to the total water footprint in the observed and optimized diets for women (Tompa et al., 2022)

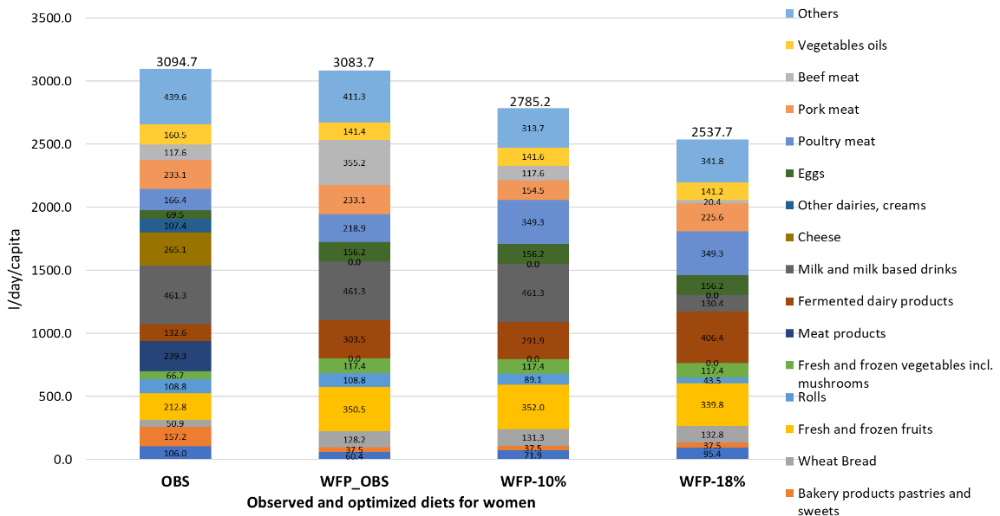


OBS = observed diet, WFP_OBS = optimized diet with no water footprint reduction, WFP-15%= optimized diet with 15% water footprint reduction, WFP-28% = optimized diet with 28% water footprint reduction

Figure 22.: Contribution of the main food groups (n = 11) to the total water footprint in the observed and optimized diets for men (Tompa et al., 2022)

In the observed diets, the total water footprint contribution showed that the pure animal-based food groups weighted the most, but not the ‘meats and products’. Instead, the ‘milk and dairies’ main group was the greatest contributor. These results are can be understood based on water footprint values and intake amounts of the food groups. Thus, ‘milk and dairies’ was the major contributor, since it is consumed in a high quantity (women: 249.8 and men: 262.7 g/day/capita) (SM Tables 4-5), and the mean water footprint value of dairies and milk is considerably higher in Hungary (cheese: 13,841 l/kg, milk: 2890 l/kg) compared to the global average (cheese: 5060 l/kg, milk: 1054 l/kg) (Mekonnen & Hoekstra, 2010a, 2010b). Besides, the intake of beef meat is relatively low on the population-level (~4.14 g/day/capita) which typically elevates the mean dietary water footprint value of the meat food group. Previous analysis on the water footprint consequences of the shift to different dietary scenarios already pointed out that just reducing the amount of meat by 50% and replacing it with dairies and eggs would not lead to a great difference either in the water footprint or in the dietary quality in Hungary (Tompa, Lakner, et al., 2020). Two purely plant-based food groups followed in the rank of total dietary water footprint contributors: ‘grains’ and ‘fruits and products’. Similarly, other studies concentrating on European countries and the total water footprint usually found meats and dairies (Capone et al., 2013; Sáez-Almendros et al., 2013; Vanham, Hoekstra & Bidoglio 2013) as the main contributors, followed by cereals and vegetable oils. On the global level, in the case of green water, meats are the main contributors, while plant-based foods (especially cereals, nuts, and sugars), for the blue water footprint. If the scenario is changed to a healthier one, plant-based foods take the place of the main contributors (Harris et al., 2020).

The analyses of dietary water footprint on the food sub-groups showed a more sophisticated picture. In the case of the observed and optimized diets for women, the greatest contributors among food sub-groups were the ‘milk and milk-based drinks’ (except in the WFP-18%). Their amount was the same as that observed for the WFP_OBS and WFP-10% models but showed a considerable decrease in the WFP-18% model. Furthermore, the water footprint contribution of ‘cheese’ and ‘meat products’ dropped to 0 l/day/capita in all optimized models. On the other hand, ‘poultry meat’ (in WFP-10% and WFP-18%), ‘fresh and frozen fruits’ (in the WFP_OBS, WFP-10%, and WFP-18% models), and ‘fermented dairy products’ (a big growth in WFP_OBS and WFP-10% and even greater in the WFP-18% model) showed a notable increase in the water footprint contribution to the total optimized diets compared to the observed diet. ‘Fermented dairies products’ became the largest contributor in the WFP-18% model for women. ‘Beef meat’ was dominant in the WFP_OBS model (but not in any other), despite its very low intake amount (9.7 g/day/capita), and pork meat represented a moderate part of the water footprint contribution in the observed and all of the optimized diets. (Figure 23.)

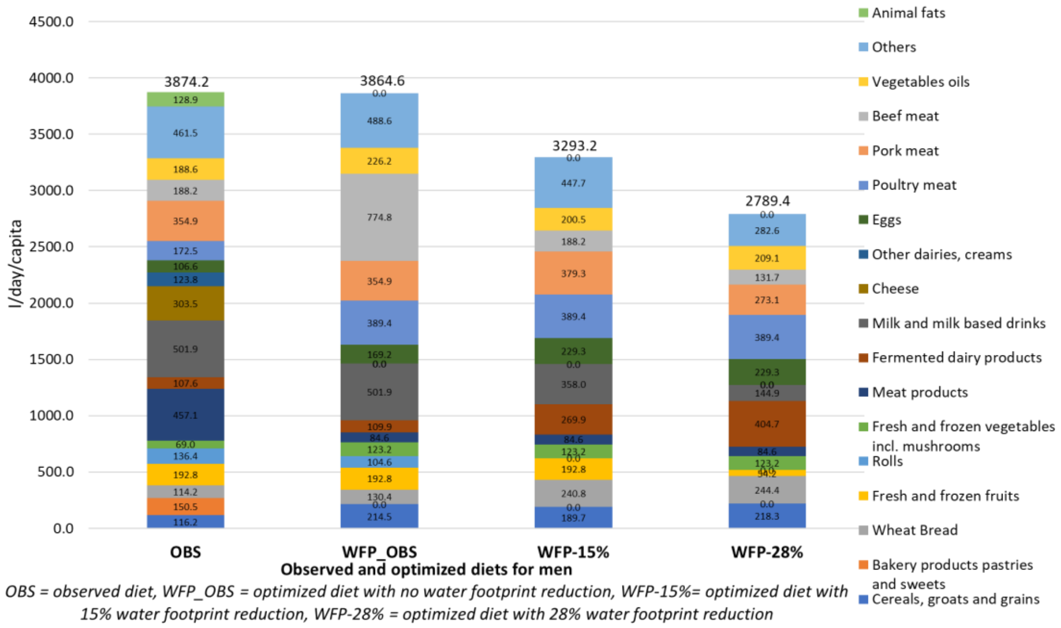


OBS = observed diet, WFP_OBS = optimized diet with no water footprint reduction, WFP-10%= optimized diet with 10% water footprint reduction, WFP-18% = optimized diet with 18% water footprint reduction

Figure 23.: Major contributors* to the total water footprint among food sub-groups (n = 17) in the observed and optimized diets for women (Tompa et al., 2022)

*Major contributors: food sub-groups that contributed to the total dietary water footprint of diets over the average of food sub-groups in the observed diet; food sub-group > mean of the dietary water footprint contribution value of the food sub-groups (88.42 l/day/capita) in the observed diet or at least one model. (The list of all food sub-groups is in the SM Table 1.)

Moreover, in the case of models for men, ‘milk and milk-based drinks’ were the greatest contributor in the observed and WFP_OBS and WFP-15% optimized diets, however, it shows a considerable stepwise reduction, until in the WFP-28% they were not the greatest contributor (‘fermented dairy products’ replaced them). ‘Fermented dairy products’ showed a stepwise growth through the optimized diets in parallel with the stepwise reduction of the water footprint. As in models for women, ‘cheese’ dropped to 0 l/day/capita in all optimized diets, while ‘meat products’ took the minimum possible value (min. constraints set as the 10th percentile), resulting in a less influential contribution to the total dietary water footprint in the optimized models. Contrarily, ‘poultry meat’ increased (max. constraints set as the 90th percentile), resulting in a heavy contribution to the total dietary water footprint in all three optimized diets. ‘Beef meet’ was the first major contributor in the WFP_OBS model, again despite its low intake (21.1 g/day/capita). In the other models its intake was somewhat low (3.6–5.1 g/day/capita), but its contribution to the total dietary water footprint was still notable (Figure 24). See further details on the 10th and 90th values in the SM, Tables 2-5.



OBS = observed diet, WFP_OBS = optimized diet with no water footprint reduction, WFP-15%= optimized diet with 15% water footprint reduction, WFP-28% = optimized diet with 28% water footprint reduction

Figure 24.: Major contributors* to the total water footprint among the food sub-groups (n = 18) in the observed and optimized diets for men (Tompa et al., 2022)

*Major contributors: food sub-groups that contributed to the total dietary water footprint of diets over the average of food sub-groups in the observed diet; food sub-group > mean of the dietary water footprint contribution value of the food sub-groups (110.69 l/day/capita) in the observed diet or at least one model. (The list of all food sub-groups is in the SM, Table 1.)

Considering the more detailed analysis of this study, it turned out that while the amount of the ‘meats and products’ group only moderately decreased as the dietary water footprint contributor (and also in weight) in the optimized diets, there was a quality change inside the group favoring the healthier choices: more poultry and less meat products (i.e., sausages) (Okostányér®, 2016). Similarly, while the contribution of ‘milk and dairies’ decreased steadily in parallel with the water footprint reduction, there was also a quality change: ‘fermented dairy products’ appeared to be the most favorable, while all other ‘milk and dairies’ sub-groups dropped (except for cottage cheese, which did not change in WFP_OBS for men and WFP_OBS and WFP-10% for women). While Lares-Michel et al. (2021) identified red and processed meat (~94 times) and milk and dairies (including cheese, milk, and yogurt) as ~ 13 times a risk factor for exceeding dietary water footprint value related to healthy diets, this analyses showed that the selection of beneficial items of food sub-groups of meat and milk dairies in the healthiness-water footprint dimension can result in an acceptable trade-off between water footprint impact a dietary quality. However, the common conclusion of these two studies is that red meats, processed meats, cheese, and milk could be complicated food sub-groups items in a water-footprint friendly and healthy diet.

5.4.3. The dietary shift towards water dietary footprint reduced, nutritionally adequate, and cultural acceptability-focused diets

The dietary shift was analysed based on both food group and food sub-groups variation, in other words, the negative or positive change of food quantities compared to the observed diets in g/day/capita. As Table 10. shows, the amount of ‘vegetables and products’, ‘grains’ and ‘eggs and products’ was elevated in all optimized diets for men and women also. ‘Fruits and products’ considerably increased in all optimized diets for women, while for men, it elevated in the WFP-15% model and decreased in the WFP-28% models. ‘Meat and products’ increased in steps 1 and 2 reductions for women and in ‘WFP_OBS’ and in and WFP-28% for men, it decreased. ‘Drinks’, ‘sweets and products’ and ‘fats and oils’ dropped in all optimized models for both men and women. ‘Milk and diaries’ also showed a considerable decrease for both sexes, except in WFP_OBS for women. ‘Sauces and seasoning did not change except the decrease in WFP-28% for men and ‘Alcoholic drinks’ either change or decreased (in WFP-10%).

Table 10.: Dietary shift: change between observed and optimized diets in g/day/capita by main food groups.

	Optimized Diets for Men			Optimized Diets for Women		
	WFP_OBS	WFP-15%	WFP-28%	WFP_OBS	WFP-10%	WFP-18%
Food groups	Change compared to the observed diet in g/day/capita					
Alcoholic drinks	0.00	-99.86	-129.95	0.00	0.00	-9.51
Drinks	-14.87	-14.87	-61.78	-46.79	-46.79	-46.79
Eggs and products	20.44	40.08	40.08	28.34	28.34	28.34
Fats and oils	-9.64	-14.59	-12.94	-13.48	-13.44	-13.51
Fruits and products	0.00	13.56	-102.00	123.20	124.51	114.27
Grains	103.23	150.14	150.14	90.92	75.67	72.13
Meats and products	20.29	7.76	-8.93	-18.91	9.21	30.52
Milk and dairies	-45.04	-45.63	-88.08	12.78	-0.42	-79.72
Sauces and seasonings	0.00	0.00	-7.17	0.00	0.00	0.00
Sweets	-38.79	-38.79	-38.00	-34.76	-34.76	-34.76
Vegetables and products	199.52	64.96	181.70	161.69	161.69	161.69

OBS = observed diet, WFP_OBS = optimized diet with no water footprint reduction, WFP-10% = optimized diet with 10% water footprint reduction, WFP-18% = optimized diet with 18% water footprint reduction, WFP-15% = optimized diet with 15% water footprint reduction, WFP-28% = optimized diet with 28% water footprint reduction. Color scale: the values are expressed in g/day/capita:

> +100	50–99.9	0.1–49.9	0.0	−49.9–−0.1	−99.9–−50	<−100

To continue with the dietary shift by main food groups, there were mainly similarities but also some differences in the variation of food sub-groups for the two sexes. Starting with the similarities, in the synergy of healthiness and dietary water footprint, the "beneficial" sub-groups that increased as a trend in optimized diets were the 'whole grain bread', 'canned vegetables and vegetable products', 'wheat bread', 'fresh and frozen vegetables incl. mushrooms', 'fermented dairy products', 'poultry meat', 'eggs', and 'nuts and seeds' (except for WFP_OBS for men). On the other hand, the food sub-groups that either decreased in all optimized models or stayed at the observed level were the following: 'bakery products, pastries, and sweets', 'fruit products', 'dry pasta', 'rolls', 'potatoes', 'jams', 'meat products', 'fruit and vegetable juices', 'sauces and seasoning', 'cottage cheese', 'cheese', 'other dairies and creams', 'offals and products', and 'animal fats'. both alcoholic and non-alcoholic drinks either decreased considerably or reached the 0 g/day/capita variation value. Some differences were found between men and women. The 'cereals, groats, and grains' sub-group grew for men but dropped for women, 'vegetable oils' increased for men but decreased for women, 'fresh and frozen fruits' showed a great increase for women but was lowered for men in step 2 reduction (WFP-28%), and 'fishes incl. canned fishes' were elevated for women but equaled to the observed value for men. Legumes did not change in quantity, except for step 2 water footprint reduction models for both sexes (WFP-18% and WFP-28%), where they increased. Furthermore, 'carbonated soft drinks' did not change for women but decreased considerably in all optimized diets for men. Besides, 'beef meat' and 'pork meat' (the red meats) showed all possible variations in the different models with small changes but lowered at the step 2 reduction for both sexes (WFP-18% and WFP-28%) (Table 11.).

Table 11.: Dietary shift: change between observed and optimized diets in g/day/capita by food sub-groups (Tompa et al., 2022).

	Optimized Diets For Men			Optimized Diets for Women		
	WFP_OBS	WFP-15%	WFP-28%	WFP_OBS	WFP-10%	WFP-18%
Food sub-groups	Change compared to the observed diet in g/day/capita					
Cereals, groats, and grains	+51.8	+38.7	+53.8	−24.0	−18.0	−5.6
Nuts and seeds	0.0	+13.6	+13.6	+13.0	+13.0	+13.0
Legumes and products	0.0	0.0	+12.4	0.0	0.0	+5.8
Whole grain bread	+49.0	+49.0	+49.0	+48.4	+48.4	+48.4
Canned vegetables and vegetable products	+57.5	+9.9	+27.2	+41.4	+55.7	+42.1
Bakery products, pastries, and sweets	−18.1	−18.1	−18.1	−14.4	−14.4	−14.4
Wheat Bread	+14.6	+114.3	+117.6	+69.8	+72.6	+74.0
Fruit products	0.0	0.0	0.0	0.0	0.0	0.0
Fresh and frozen fruits	0.0	0.0	−115.6	+114.8	+116.1	+105.8
Dry pasta	0.0	0.0	−18.4	−3.3	−19.8	−19.8
Rolls	−12.1	−51.9	−51.9	0.0	−7.5	−24.8
Fresh and frozen vegetables(incl. mushrooms	+142.1	+142.1	+142.1	+132.9	+132.9	+132.9
Potatoes	0.0	−87.0	0.0	−12.7	−26.9	−19.2
Jams	0.0	0.0	0.0	−4.6	−4.6	−4.6
Fruit and vegetable juices	0.0	0.0	−46.9	0.0	0.0	0.0
Sauces and seasonings	0.0	0.0	−7.2	0.0	0.0	0.0
Meat products	−66.1	−66.1	−66.1	−42.4	−42.4	−42.4
Fermented dairy products	+0.7	+49.9	+91.4	+52.6	+49.0	+84.2
Milk and milk-based drinks	0.0	−49.8	−123.5	0.0	0.0	−114.5
Cottage cheese	0.0	0.0	−10.2	0.0	−9.6	−9.6
Cheese	−21.9	−21.9	−21.9	−19.2	−19.2	−19.2
Other dairies creams	−23.8	−23.8	−23.8	−20.6	−20.6	−20.6
Eggs	+20.4	+40.1	+40.1	+28.3	+28.3	+28.3
Poultry meat	+70.4	+70.4	+70.4	+17.0	+59.4	+59.4
Pork meat	0.0	+3.5	−11.7	0.0	−11.2	−1.1
Beef meat	+16.0	0.0	−1.5	+6.5	0.0	−2.7
Fishes inc. canned fishes	0.0	0.0	0.0	0.0	+3.5	+17.3
Offals and products	0.0	0.0	0.0	0.0	0.0	0.0
Animal fats	−16.9	−16.9	−16.9	−9.8	−9.8	−9.8
Vegetable oils	+7.3	+2.3	+3.9	−3.7	−3.6	−3.7
Sugar and honey	−20.7	−20.7	−19.9	−20.4	−20.4	−20.4
Wines	0.0	0.0	−30.1	0.0	0.0	−9.5
Beers	0.0	−99.9	−99.9	0.0	0.0	0.0
Carbonated soft drinks	0.0	0.0	0.0	−42.2	−42.2	−42.2
Smoothies	−14.9	−14.9	−14.9	−4.6	−4.6	−4.6

OBS = observed diet, WFP_OBS = optimized diet with no water footprint reduction, WFP-10% = optimized diet with 10% water footprint reduction, WFP-18% = optimized diet with 18% water footprint reduction, WFP-15% = optimized diet with 15% water footprint reduction, WFP-28% = optimized diet with 28% water footprint reduction. Color scale: the values are expressed in g/day/capita:

> +100	50–99.9	0.1–49.9	0.0	−49.9–−0.1	−99.9–−50	<−100

A diverse picture characterized the dietary shift between the observed and optimized diets. In the dimension of the health-dietary water footprint, the most beneficial main food groups were the ‘grains’, ‘eggs and products’, and ‘vegetables and products’, which showed a clear growth—

and varying only slightly—in all models for both sexes. ‘Fruits and products’ showed a great difference between the sexes: steadily increased for women and steadily decreased for men, which could be explained by the fact the ‘cereals, groats, and grains’ grew more for men to cover dietary fiber requirements, that were one of the most binding nutrient constraints. Besides, ‘fruits and products’ has relatively high blue water footprint values (Meier & Christen, 2012; Scheelbeek et al., 2020; Tompa, Lakner, et al., 2020). Thus, these two factors could explain why the model did not favor ‘fruits and products in case of the greatest water footprint reduction model (WFP-28% for men). Except for ‘fruits and products’, these results are mostly in line with the review results of Steenson and Buttriss (2021); grains, cereals, vegetables, and fruits seemed to be advantageous in the environment–health synergy most of the time, while eggs were less advantageous. They concluded that in optimization studies, the results on eggs and milk and dairies are inconsistent, probably due to the trade-offs of environmental burden and nutrient content. Legumes and nuts seemed mostly beneficial, and they were also favored in this study: ‘nuts and seeds’ were elevated in most models, while ‘legumes’ only in the step 2 water footprint reduction models (WFP-18% and WFP-28%). On the other hand, ‘drinks’, ‘fats and oils’, ‘sweets’, ‘alcoholic drinks’, and ‘milk and dairies’ (the latter is an exception in WFP_OBS for women) dropped as a trend meaning that they are non-beneficial regarding the healthiness and dietary water footprint synergies that are supported by Steenson and Buttriss’ (2021) findings. The results partly agree with Chaudhary and Krishna’s (2019) sustainable diet optimization, which resulted in the elevation of fruits and vegetables and pulses and roots, while cereals did not change and meat, dairies, and eggs decreased in Europe and Central Asia. Regarding Hungary, the main differences with this study were that the meat groups did not decrease drastically, and the eggs and products were elevated in each case, which could be due to the methodological differences, especially since they included five environmental metrics (Chaudhary & Krishna, 2019). Contrary to Steenson and Buttriss’ (2021) summary, meats groups showed a versatile picture: they were increased in the WFP_OBS models, decreased slightly for men, and increased for women (originated in the growth of the poultries sub-group) in the step 2 models reducing the water footprint. Besides, a quality change could be observed: ‘poultry meat’ increased, while ‘meat products’ fell to a minimum, and the trend for ‘pork meat’ and ‘beef meat’ showed a small variation. However, both red meats dropped for the step 2 water footprint reduction. Regarding ‘milk and dairies’, the models favored ‘fermented products’, while all others dropped (except for ‘cottage cheese’ in WFP_OBS and WFP-15% for men, and WFP_OBS for women), which is similar to the tendency found in other studies, except for fermented dairies. The difference with the mentioned studies could be that, besides the methodological differences, these studies have only accounted for the water footprint (especially including green water) and have not conducted in-depth analyses on the food sub-groups(Steenson

& Buttriss, 2021). Also, while coming from a different origin, the results of this study is agreeing with van Dooren, Man, Seves, and Biesbroek (2021) conclusions that a low meat content diet could be more sustainable (than vegetarian), since the production of meats and products milk and dairies are linked and a lower amount of intake that is in line with the co-production could be a direction. Furthermore, the necessary amount of offals would go hand in hand with the other animal-based food productions according to the 'nose to tail' animal consumption approach. Furthermore, the harmonization of milk and dairy products with the water footprint friendly and healthy food consumption would further lead to environmental and health benefits (Nagypál et al., 2020).

These trends, emphasizing the quality change in the 'meats and products' and 'milk and dairies' groups, are in line with the Hungarian FBDG to choose lean meat (e.g., poultries) and dairies (e.g., fermented dairies) more often than high-fat content ones. Nevertheless, the Hungarian population's nutrition is characterized by high total fat and SFA intake (Sarkadi Nagy et al., 2017). Furthermore, these results also agree with the Hungarian FBDG to avoid products with high added sugar content ('sweets'), keep eggs and fish in the diet to make protein sources more diverse, and eat plenty of grains, vegetables, and fruits. 'Fruits and products' might be an exception, but the drop between the observed and the step 2 reduction for men (WFP-28%) did not equal a 0 value. The intake amount of the 'fruits and products' group was still 76–178 g/day/capita in the optimized models for men, and most of it was the 'fresh and frozen fruits' sub-group (SM Tables 2-5.). Besides, in the WFP-28% model, where the 'fruits and products' group was decreased, the overall amount of fruits and vegetables was 568.9 g/day/capita (SM Table 5.), which is above the recommendation (Okostányér®, 2016). Even though the lowering of the 'fruits and products' group is reasonable in step 2 dietary water footprint reduction for men (WFP-28) due to the blue water 'cost', it cannot be recommended as a dietary shift to a healthier diet. The optimized intake of red meats (beef and pork meat) is also in line with the Hungarian FBDG: the daily intake amount in the optimized diets for women was between 25.2 g/day/capita (WFP_OBS) and 41.9 g/day/capita (WFP-10%) and for men between 42.6 g/day/capita (WFP_OBS) and 71.7 g/day/capita (WFP-28%), which is similar to, or lower than, the maximum national recommendation of 50–71.4 g/day/capita (Okostányér®, 2016) and lower than the Swedish sustainable diet recommendation of maximum 500g/week (Fischer & Garnett, 2016). The drop in the intake amount of 'milk and dairies' in the optimized diets could conflict with the recommendation of the Hungarian FBDG because of the 500 mg/day/capita calcium equivalent intake from milk-based sources (Okostányér®, 2016), adding that calcium was only a problematic nutrient in the WFP-18% model for women and that the 'milk and dairies' sub-group was still in the range of 170.1–262.6 g/day/capita in the optimized models (SM Table 4-5.). Finally, these results support the conclusion that a shift to the recommended diet with specifications in the food sub-groups could simultaneously provide health and dietary water footprint benefits (Alessandra, 2014; Capone et al., 2013; Harris et al., 2020; Jalava et al., 2014; Sáez-Almendros et al., 2013; Tom et al., 2016; Tompa, Lakner, et al., 2020; Vanham, Hoekstra & Bidoglio, 2013; Vanham, Mekonnen & Hoekstra 2013).

5.4.4. Problematic nutrients in the water footprint reduced, nutritionally adequate and cultural acceptability-focused diets

Nutrients were classified as "problematic" (i.e. binding) if they reached the minimum or maximum constraint in the model, meaning that it was difficult to fulfill their required value in the optimization process. For both sexes, energy and sodium reached the maximum value in all optimized diets; in addition, the maximum limit of total fat in the WFP-28% model for men was also realized. On the other hand, dietary fiber was the only nutrient that was at the minimum constraint value in all models for both sexes. For women, vitamin B12 was at the minimum value in each optimized diet, while calcium, iron, zinc, and potassium were also at the bottom limit in step 2, the maximum water footprint reduction model (WFP-18%). In models for men, vitamin D in WFP_OBS and WFP-28% models and zinc in WFP-28% equaled the minimum constraint value (Table 12.)

Table 12.: Binding nutrients: evaluation of nutritional adequacy constraints expressed as % of the RDI (Tompa et al., 2022)

			Women				Men			
Nutrients	Unit	Type of constraint	RDI	WFP_OBS	WFP-10%	WFP-18%	RDI	WFP_OBS	WFP-15%	WFP-28%
				% of RDI				% of RDI		
Energy	kcal/day	max	2000	100.0	100.0	100.0	2600	100.0	100.0	100.0
Energy	kcal/day	min	1700	117.6	117.6	117.6	2300	113.0	113.0	113.0
Total dietary fibers	g/day	min	25	100.0	100.0	100.0	25	100.0	100.0	100.0
Vitamin-A, RAE	µg/day	min	650	176.3	178.8	166.4	750	185.3	172.7	154.5
Vitamin-A, RAE	µg/day	max	3000	38.2	38.7	36.1	3000	46.3	43.2	38.6
Thiamin	mg/day	min	0.9	237.5	227.2	226.0	1.1	241.4	257.1	255.4
Riboflavin	mg/day	min	1.3	163.9	163.3	157.7	1.6	155.1	165.8	160.3
Vitamin-B6	mg/day	min	1.1	211.7	208.3	212.2	1.5	193.0	170.5	171.5
Vitamin-B6	mg/day	max	25	9.3	9.2	9.3	25	11.6	10.2	10.3
Folate, DFE_	µg/day	min	330	187.9	185.8	189.8	330	249.4	275.7	283.8
Folate, DFE	µg/day	max	1000	62.0	61.3	62.6	1000	82.3	91.0	93.6
Vitamin-B12	µg/day	min	4	100.1	100.1	100.1	4	128.8	121.9	112.9
Vitamin-C	mg/day	min	95	146.3	145.0	145.0	110	118.3	108.0	100.5
Vitamin-D	µg/day	min	4	121.1	124.8	129.5	5	100.0	107.2	100.0
Vitamin-D	µg/day	max	100	4.8	5.0	5.2	100	5.0	5.4	5.0
Vitamin-E	mg/day	min	11	148.1	149.2	149.7	13	159.6	157.9	161.8
Vitamin-E	mg/day	max	300	5.4	5.5	5.5	300	6.9	6.8	7.0
Calcium	mg/day	min	950	112.1	110.7	100.0	950	105.6	125.0	121.1
Calcium	mg/day	max	2500	42.6	42.1	38.0	2500	40.1	47.5	46.0
Phosphorus	mg/day	min	550	255.8	262.9	262.3	550	308.8	318.8	312.2
Magnesium	mg/day	min	300	110.9	111.4	111.5	350	104.0	106.3	107.2
Iron	mg/day	min	16	100.3	100.3	100.0	11	182.4	195.1	198.7
Zinc	mg/day	min	10.1	100.1	100.1	100.0	12.9	100.4	100.3	100.0
Zinc	mg/day	max	25	40.5	40.5	40.4	25	51.6	51.6	51.4
Potassium	mg/day	min	3100	100.5	100.5	100.1	3100	109.9	101.4	100.6
Sodium	mg/day	min	575	417.5	417.5	417.5	575	543.5	542.8	542.6
Sodium	mg/day	max	2400	100.0	100.0	100.0	3120	100.2	100.0	100.0
Total protein	E%	min	15	121.3	128.0	131.5	15	123.4	126.8	122.5
Total carbohydrate	E%	min	45	109.6	107.5	106.9	45	107.8	106.8	109.3
Total carbohydrate	E%	max	60	82.2	80.6	80.2	60	80.8	80.1	82.0
Total fat	E%	min	20	171.4	172.6	173.4	20	170.4	173.3	175.0
Total fat	E%	max	35	97.9	98.6	99.1	35	97.4	99.0	100.0
Saturated fatty acids	E%	max	10	69.9	69.1	66.5	10	68.3	66.9	66.2
Polyunsaturated fatty acids	E%	min	6	223.6	223.6	224.5	6	219.1	222.8	225.0
Added sugars	E%	max	10	23.2	22.9	25.4	10	28.0	30.6	30.1

Red: equals maximum constraint, Yellow: equals minimum constrain

The maximum energy constraint was problematic in each model, which could be because energy and nutrient-dense foods are advantageous in the models (Darmon et al., 2003). Comparing the two sexes, a greater reduction of the total dietary water footprint was possible for men (women: 18% and men: 28%), since the higher energy range (2300–2600 kcal versus 1700–2000 kcal for women) of diets provided more space for a feasible solution. Besides, the minimum constraint on dietary fibers and the maximum on sodium were also binding in each model for both sexes, which is in agreement with the Hungarian population intake, which is typically low in dietary fibers (Sarkadi Nagy et al., 2017) and high in sodium (Nagy et al., 2017). For women, the minimum limit for vitamin B12 in each model and potassium, iron, and zinc in WFP-18% were binding constraints, demonstrating that the greater the reduction in the dietary water footprint, the more binding the nutrients. The potassium, zinc, and iron intake of women is indeed a problem on the population-level, but the B12 intake is adequate (Nagy et al., 2017; Schreiberné Molnár et al., 2017). The reason for this could be that otherwise nutritionally and/or environmentally non-beneficial food groups (e.g., meat products, offals, cheese) were limited or decreased in the models that are a common source of the intake of vitamin B12. For men, the minimum constraint of vitamin D (WFP-28%) and zinc (WFP_OBS and WFP-28%) and the maximum for total fat (WFP-28%) were limiting factors. The population intake is problematic in the case of each nutrient, and, again, the step 2 reduction in the dietary water footprint meant that the limit in nutrient constraints was reached. Similarly, Perignon et al. (2016b) found that the stepwise lowering of dietary GHGE at the point of a 30% reduction and nutritional adequacy (with cultural acceptability constraints) in the optimized diet led to the lower limit for dietary fibers, vitamin D, and zinc, while the upper limit for SFA and sodium were also problematic, among others. With further GHGE reduction, more problematic nutrients could be identified. These results point to the conclusion that the higher the reduction in environmental impact, the more trade-offs should be taken into consideration (e.g., micronutrient deficiency and cultural acceptability) and controlled by the constraints or output measures (Gazan, Brouzes et al., 2018).

5.4.5. New Scientific Results

NSR$_1$: With sustainable diet optimization – based on linear programming – I estimated the possible total dietary water footprint (green, blue, and grey) reduction (– 18% for women and –28% for men) in optimized diets designed to be nutritionally adequate and cultural-acceptability-focused (dietary shift: ~ 32%) on the Hungarian population-level.

NSR $_2$: I estimated the major total (green, blue, and grey) dietary water footprint contributors to the observed and optimized (water footprint reduced, nutritionally adequate, and cultural-acceptability-focused) diets among main food groups and food sub-groups separately for men and women on the Hungarian population-level.

NSR $_3$: Based on the health and blue and green water footprint impact analysis of baseline (observed diet) and alternative dietary scenarios, I identified that the “sustainable scenario” (adapted from the “planetary healthy diet” (Willet et al. (2019) to the Hungarian population) as the most advantageous dietary scenario to shift towards (+9% in dietary quality, −41.7% in green water footprint, and −28.9% in blue water footprint).

NSR $_4$: With sustainable diet optimization – based on linear programming – I described the possible dietary shift towards the dietary water footprint-reduced, nutritionally adequate and cultural-acceptability-focused diets by identifying the main food groups and sub-groups to be limited or increased compared to the observed, representative Hungarian diets, separately for both sexes.

NSR $_5$: Based on the most consumed foods and food categories in Hungary, I identified the association between nutrition composition and food-related blue and green water footprint, furthermore, I identified nutrients as indicators based on their food-related water footprint and inadequate or excessive intake level on the population-level.

NSR $_6$: I identified nutrients at risk for deficiency or excess intake on the population-level in the case of the dietary shift towards dietary water footprint-reduced, nutritionally adequate, and culturally acceptably diets, separately for both sexes.

6. CONCLUSIONS AND RECOMMENDATIONS

Conclusion and recommendation are written as the fusion of the studies (S_1-S_4) included in the dissertation. The conclusions are valid for (1) food related/dietary water footprint, (2) nutritional/dietary quality and (3) cultural acceptability among the sustainable nutrition dimensions, besides, they are representative for the Hungarian population.

6.1. Observed dietary water footprint and major contributors among foods on the population-level

The observed total dietary water footprint was 3094.7 l/d/c (green WFP: 2710.3; blue WFP: 62.0 l/d/c) for women and 3874.4 l/d/c (green WFP: 3367.7; blue WFP: 78.4 l/d/c) for men (S_4). By averaging the values of the two sexes (3484 l/d/c) results are somewhat lower than multi-country estimations including Hungary among other countries; the work of Gibin et al. 2022 resulted in 3959.1 l/d/c for Hungary among EU countries, Jalava et al.'s (2014) global-scale estimation was 3899.2 l/d/c for Hungary, Vanham, Hoekstra & Bidoglio (2013) described 4053 l/d/c for the Eastern European region, while Harris et al. (2020) meta-analysis estimated a rough range of 2873-3792 l/capita/day for European countries (with or without the inclusion of grey water footprint). Consequently, the estimated total dietary water footprint of Hungary is in the upper range of the European average. Regarding the observed dietary water footprint values, besides the varying methodological solutions, the difference in the estimation could be caused by three main reasons: (1) the other estimations are based on the FAO FBS database (that is a food supply database with related conversion factors) and/or EFSA food consumption database, while the estimation of S_4 relies on the HDNSS 2014 dietary survey data, (2) all other estimation averaged meats in one main food group, however, beef meat predominantly elevates the mean dietary water footprint of meats food groups to a high level (Gallo, Landro, Grassa, & Turconi, 2022; Gibin et al., 2022; Harris et al., 2020; Jalava et al., 2014; Vanham, Hoekstra & Bidoglio 2013). In Hungary, the meat consumption is relatively high (178.3 g/d/c on average for both sexes) but just a small share of it is beef meat (4.2 g/d/c), (3) in the estimation of S_4, there was 277g/d/c food categorized as "others" excluded since they were numerous different ultra-processed items (e.g. soup powder, pudding powder) under < 4g/d/c that was exclusion criteria as well as was impossible to estimate correct water footprint values from the database (Mekonnen & Hoekstra, 2010a, 2010b) and lastly, (4) there were no sex-specific estimations included in the other studies.

The proportion of blue water footprint was ~ 2-3% in the observed diets (Harris et al., 2020),(S4) as well as in optimized water-footprint-reduced, cultural-acceptability focused diets for both sexes. It means that the consideration of green and or grey water footprint is especially important in the case of Hungary since most of the water used for food production is green (86-87%) so the food system is heavily relying on it (S_4). Furthermore, as highlighted by the EC, sustainable water management would be a critical issue for Hungary due to the expected climate change impact (EC, 2022b). The predictions for climate change are inconsistent but agree on one thing: the weather and seasons will be more unpredictable and radical that is why the management of green water should be but in special focus (Kemény, Lámfalusi & Molnár, 2018), furthermore, Hungary's territory is significantly exposed to climate change impact resulting drought and floods (EC, 2022b).

The population-specific weighted average of blue and green water footprint of the main food groups shows that meats and products are with the highest value, however, milk and dairies, fats and oils, and sweets are high in food-related green water footprint, while fruits in blue water footprint (S_3). It has been well described in international studies that fruits and juices are the "hidden" contributors to the blue water footprint (Lares-Michel et al., 2021; Meier & Christen, 2012; Scheelbeek et al., 2020; Tepper et al., 2022). In the case of the blue water footprint, the relevance of grains is greater than in the green water footprint: its weighted average is close to the level of fats and oils and milk and dairies. Vegetables are low in both blue and green food-related water footprint. On the global scale of total water footprint values, meats predominantly have the highest values sharing the rank with nuts (2nd after bovine meat!), butter, pulses, and eggs (Gallo et al., 2022). The picture is more sophisticated if the dietary water footprint contributions of the food groups and sub-groups are considered that means do not just have their water footprint value but their population intake as well (see just below) (S_3).

The evaluation of the dietary water footprint of the observed diets on the population-level showed the following results: milk and dairies (men: 1125.9; women: 1050.3 l/d/c) and meats and meat products (men: 1195.8; women: 772.6 l/d/c) contributed the most to the total dietary water footprint, followed by grains for (men: 415.3, women 311 l/d/c) and fruits and products (men: 218.2, women: 242.9 l/d/c). On the food sub-group level milk and milk-based drinks (women: 461.3; men: 501.9 l/d/c), cheese (women: 265.1; men: 303.5 l/d/c), meat products (women: 239.3; men: 457.1 l/d/c), pork meat (women: 233.1; men: 354.9 l/d/c) and fresh and frozen fruits (women: 212.8; men: 192.8 l/d/c) were the major contributors to the dietary water footprint in the observed diet on the population-level (S_4). That is, in a part, different from results on the European and global-level (Gibin et al., 2022; Harris et al., 2020; Jalava et al., 2014; Lares-Michel et al., 2021; Steenson & Buttriss, 2021), where meats are usually the greatest dietary water footprint contributors followed by the milk and dairies, it can be concluded that the dietary water footprint contribution of milk and dairies in Hungary is of significant importance that was also supported by an international study among European countries (Gibin et al., 2022). The reasons for it are double fold: the high intake of milk and dairies in the population (278.8 g/d/c) and their related dietary water footprint is higher compared to the global average (Hungary: cheese: 13841 l/kg, milk: 2890 l/kg; global average: cheese: 5060 l/kg, milk: 1054 l/kg (Mekonnen & Hoekstra, 2010a, 2010b)) as well as the low intake of beef that lower the weighted average of the meats group. On the other hand, diets optimized to be water footprint-reduced, nutritionally adequate, and culturally acceptability-focused revealed by in-depth analysis that a food sub-group may be beneficial (poultries, fermented dairy) or non-beneficial (cheese, processed meats) in the health-water footprint synergy despite their classification in an otherwise major dietary water footprint contributor main food group (S_4).

6.2. Possible reduction of dietary water footprint by dietary changes on the population-level

By using a well-designed, country- and context-specific model, considerable total dietary water footprint reduction was possible (~ 23.9 % on average for both sexes) besides providing nutritional adequacy and respecting cultural acceptability (~ 32% dietary shift) and without pre-defined plant-based scenarios and pre-or post-exclusion of whole food groups, thus it can be stated that diet optimization is an ideal tool to resolve sustainable diet problems (Gazan, Brouzes et al., 2018; van Dooren, 2018) (S_4). Although there have been diet optimization studies published about the reduction of dietary water footprint on a multi-country level, they have not included green and/or grey water footprint in the analyses, have not applied country-specific databases (Hungarian or European RDIs), used several environmental impact categories that might cover the effect on water footprint, or only estimated a rough range of dietary water footprint reduction, thus no data can directly be compered (Chaudhary & Krishna, 2019; Jalava et al., 2014).

The dietary water footprint impact assessment on dietary scenarios pointed out that the analysis of alternative pre-defined dietary scenarios gives a broad picture but works as a trial-and-error experiment: the results clearly show that from an increase to a huge volume of dietary water footprint decrease is possible, with other words, results are considerable varying, even within the reduced animal-based food scenario categories (sustainable scenario: blue WFP: − 28.9%, green WFP: − 41.7%; cardioprotective scenario blue WFP: + 24,9, green WFP: − 20.1%; reduced-meat scenario: blue WFP: −7.3%, green WFP: − 6.1%; vegetarian scenario: blue WFP: − 14.6%, green WFP: − 12.1%; vegan scenario: blue WFP: − 44.4%, green WFP: − 66.6% on average for both sexes) (S_3). These inconsistencies are also described in the literature where the water footprint results showed great variance in dietary scenario analyses especially in the case of blue water footprint (Harris et al., 2020; Springmann et al., 2018; Steenson & Buttriss, 2021; Tom et al., 2016; Tompa, Lakner, et al., 2020) according to the meta-analysis of Harris et al (2020), in average, the estimated dietary shift results in case of no animal-based food diet (– 11.6% in blue, – 26.1% in green and – 25.2% in total dietary water footprint), ~ – 18% in reduced-meat diets and ~ – 6% in blue, green, and total dietary water footprint in case of healthier diets on the global level.

6.3. Towards the healthier, water footprint friendly, and culturally acceptable diets

Based on the health and water footprint impact assessment of baseline and alternative dietary scenarios on the population-level, the "sustainable scenario" was regarded as the most beneficial in these aspects (+9% in dietary quality, −41.7% in green water footprint, and −28.9% in blue water footprint) compared to the populational observed diets on average of both sexes. The sustainable scenario was adapted to the Hungarian population from the EAT–Lancet Commission's publications (planetary healthy diet) (Willett et al., 2019) and is characterized by − in comparison with the observed diets in the population −: more diverse intake sources of proteins, lower intake of meat and milk and diaries, higher intake of plant-based proteins, vegetables and fruits and similar grains, fats and oils content (with the preference of vegetable oils over animal fats), sweets and alcohols were standardized close to the observed level since there was no quantified recommendation for them besides the "as low as possible" principle (S_3). The possible advantages to adapt this scenario on the national level was also supported by the study of Tepper et al. (2022).

The dietary shift from the observed to the optimized diets on the population-level was estimated by a sustainable diet optimization model designed to be nutritionally adequate, water footprint-reduced, and cultural acceptability-focused. From the results, the conclusion can be drawn that the dietary shift at the food levels is not as simple as more plant-based foods and less animal-based foods, but more sophisticated details were revealed at the maximum dietary water footprint reduction level. The key funding about the dietary shift is that, among meats and milk and dairies, the ultra-processed and fatty products should be limited (e.g. sausages and cheese), while the lean and low-level processed products (e.g. fermented dairies and poultry meat) should be increased in the diet instead. Besides, a clear disadvantage of alcoholic and non-alcoholic drinks was proven: while the necessity to limit alcoholic drinks seems obvious regarding their status as behavioral risks of NCDs (IHM, 2019), the same is not true about non-alcoholic drinks. The disadvantage of drinks lies in the high fruit content of juices that are the "hidden" but great contributors to dietary water footprint (Lares-Michel et al., 2021) due to their high blue footprint of them in addition to that they have no advantage versus fresh fruits in the aspect of health in general. Furthermore, drinks often contain a high amount of added sugars, which is another identified dietary contributor to NCDs (IHM, 2019). Other food sub-groups high in added sugars should be limited (bakery products, pastries, and sweets, honey and sugars, jams, and carbonated soft drinks). Vegetables and grains and cereals showed a beneficial picture in general, proving their place as the base of the dietary pyramid for the population in the healthier and water footprint friendly diets as well and should be consumed in higher amount – especially – because of the dietary fibers content. Besides, eggs, nuts and legumes should be recommended to increase in the diet, since they are a good source of dietary protein, making the diet more diverse in that aspect and beneficial in the means of dietary water footprint. Fruits and products dropped for men that are not to be recommended, however, reasonable due to blue water footprint cost. Among oils and fats, animal fats considerably dropped for both sexes, while vegetable oils slightly grew for men and dropped for women, that could be due to the more advantageous fatty-acid profile of plant-based oils (S_4). These results partly agree with studies analysing dietary shift toward more sustainable diets; Chaudhary and Krishna's (2019) diet optimization study (increased plant-based and decreased animal-based foods) and Steenson and Buttriss' (2021) review (plant-based foods increase, meats decrease, and eggs and milk and dairies are inconsistent). However, these conclusions are not focused on Hungary and included other environmental impact factors besides water footprint (Chaudhary & Krishna, 2019; Steenson & Buttriss, 2021).

It can be stated that despite the well-described advantages of plant-based dietary scenarios (Hallström et al., 2015; Harris et al., 2020; Jones et al., 2016; Springmann et al., 2018; Steenson & Buttriss, 2021; Vanham, Hoekstra & Bidoglio, 2013; Vanham, Mekonnen & Hoekstra 2013, 2013b; Vettori et al., 2021) in the literature, a reduced-meat (especially red and processed meat) alternative dietary scenarios could serve a more realistic, thus more sustainable alternative, especially because the pre-or post-analysis exclusion of any food groups would be necessary. A radical change towards plant-based dietary scenarios would violate social acceptability (Gazan, Brouzes et al., 2018; Perignon et al., 2016a; van Dooren, 2018; Vieux et al., 2020) as well as would pose a considerable risk for micro-nutrient deficiency on a population-level, especially that most studies have not calculated bio-availability that favors animal-based in sustainable diets (BDA, 2018; Dave et al., 2021; Gazan, Brouzes et al., 2018; Perignon et al., 2016a; Scarborough et al., 2012). Furthermore, restrictive and plant-based diets would not necessarily be more environmentally friendly, especially if analyses of blue water footprint separately considered because the high amount of nuts and legumes – as a replacement for animal-based protein – would cause an increase in consumption (Gallo et al., 2022; Springmann et al., 2018; Steenson & Buttriss, 2021; Tepper et al., 2022; Tom et al., 2016; Tompa, Lakner, et al., 2020; Vanham et al., 2020), this was proved in this work (S_3, S_4) and for studies analyses dietary GHGE as well (Perignon et al., 2016b; Vieux et al., 2020). In addition, in Hungary, the relevance of milk and dairies are major in the case of dietary water footprint, since they are the greatest contributors to the total observed dietary water forint, to simply replace meats with dairies and eggs in the vegetarian diet (with standardized energy content) would lead to no considerable water footprint and dietary quality change (S_3).

The described advantages of a reduced-meat (especially red and processed meat) dietary scenario consist predominantly of lean meat and dairies are also supported by the role of protein and energy as nutritional quality indicators. Both of them show a clear correlation with dietary water footprint (Lares-Michel et al., 2021), (S1, S_2), while the lowering of protein intake cannot be recommended, since the Hungarian population intake is adequate, the source of it should be adjusted towards healthier and lower food-related water footprint alternatives. On the other hand, the energy intake of the population is higher than recommended, moreover, the prevalence of overweight and obesity is around ~ 2/3 of the population (Sarkadi Nagy et al., 2016). The conclusion, as supported by other population studies (Lares-Michel et al., 2021) is clear, the adequate, lower than observed dietary energy intake could be recommended, especially by avoiding the unnecessary but energy-dense foods such as sweets and salty snacks, thus this change would simultaneously lead to water footprint and health benefits. Similarly, total fat showed a positive correlation with food-related water footprint (S_1, S_2), animal-based protein sources (meats and dairies and their products) with high-fat content were proven non-beneficial and total fat was identified as a problematic nutrient in the case of men, at maximal water footprint reduction optimized diet (S_4) thus the limited intake of them is supported from different dietary levels in the aspect of health and water footprint synergy. Also, SFA should be mentioned in the association of protein and energy content of foods, since it also showed a strong correlation with dietary water footprint (S1, S2), overconsumed by the population (Sarkadi Nagy et al., 2017), and identified as dietary contributing factors towards NCDs (IHM, 2019). The results at the food level also supported the conclusion that foods high in SFA should be limited: animal fats, meats, and dairies with high SFA content. As it follows from this argument, eggs are the "black sheeps" (or white among black ones?) in the animal-based protein sources that were beneficial in optimized models (S_4) and not especially high in total fat and SFA, thus could be beneficial protein sources and lower than observed intake of them cannot be recommended based on these results.

Furthermore, the assessment of a healthier, water footprint-reduced, and cultural acceptability-focused diet revealed the importance of the following consideration on the nutrient level. Calcium is under-consumed in the population (Nagy et al., 2017) and was identified as a binding nutrient at maximal water footprint reduction for women (S_4). Since the best dietary source of calcium are the milk and dairies (and recommended by the national FBDG (Okostányér®, 2016)) that are also the greatest contributor to the dietary water footprint, the consideration of calcium intake (especially) for women would be one of the risks to assess in case of water-footprint-reduced diets. The best option for non-dairy source calcium intake are the nuts, however, they also have high-water footprint values (Gallo et al., 2022), thus the population intake of calcium should be a focused issue in water footprint friendly and healthier dietary recommendation. Similarly, identified as a considerable dietary factor, B12 density of foods showed a positive correlation with blue and green food-related water footprint and over-consumed by the population (Schreiberné Molnár et al., 2017), however, in the case of the maximal water-footprint reduced diets, it was identified as binding nutrient reaching the minimum threshold (S4). It is probably due to the disadvantageous foods (meat products, offals, cheese) that are consumed in higher amounts, dense in vitamin-B12 but disadvantageous in the health-dietary water footprint synergy. Vitamin C intake is higher than recommended in the population (Schreiberné Molnár et al., 2017) and showed a negative correlation with food-related green water footprint and no significant correlation with blue water, even though positive correlation with blue water footprint could be expected due to the high blue water footprint values of fresh fruits as good vitamin-C sources (S_1). Due to the latter, vitamin-C intake should be considered when diets are focused on reducing blue dietary water footprint. The upper limit for sodium intake was a binding constraint in all optimized models (S_4) and it is chronically and extremely overconsumed in the population (Nagy et al., 2017). It also showed a positive correlation with the total, diet-related water footprint in S_2 (however, it is not a representative sample). The health and dietary water footprint consideration is clearly direct towards the limited intake of it, as it was already pushed by legislative methods (National Tax and Custom Administration, 2011; Okostányér®, 2016; Ministry of Human Capacities, 2014.), however, regarding cultural acceptability, to reach the lower intake of sodium causes a real challenge due to taste preference and high consumption of processed foods that contain a large amount of it (Kiss, Popp, Oláh, & Lakner, 2019). Dietary fibers showed a negative association with green water footprint and they are under-consumed in the population (Sarkadi Nagy et al., 2017), consequently, it was binding nutrients in all optimized diets (S_4), thus the adequate intake of them should be especially considered in water-footprint reduced diets. Iron, zinc, and potassium for women and zinc and vitamin D for men are under-consumed (Nagy et al., 2017; Schreiberné

Molnár et al., 2017) and were binding nutrients in the maximum water footprint optimized diets (S_4), thus a special focus should put on the intake of them too.

6.4. Differences based on sex as an aspect

Since women and men have different food consumption patterns (both in quantity and quality) and RDIs, there are different consequences besides similar ones for them when shift towards more sustainable diets are aimed. As S3 showed, there were greater differences in the water footprint of scenarios in the male compared to the female scenarios. This derives from the simple fact that the energy density has a great effect on the dietary water footprint values, since the more energy we consume, the more water is used for food production (Lares-Michel et al., 2021). In the dietary scenario analysis, the main conclusion was similar for the two sexes (S3), regardless of the detailed analysis of green and blue water footprint and health impact, the “sustainable scenarios” were the most advantageous. Meier and Christen (2012) analysed the difference between of sexes, although they applied a quite different approach. They concluded that the blue water use of food consumption was very similar for both sexes, considering that in the case of other environmental impact factors (i.e. GHGE, land use, NH3 emission) this difference was greater between the two genders. The reason for this lies in the structure of food consumption; while men consume more animal-based groups, women tend to consume more fruits, whose contribution to blue water use is considerable. Despite the latter finding, in S_4, the fruits and products elevated for women but decreased for men and the explanation for this is more likely that in the case of men grains and vegetables elevated to fulfill the specific RDI constraints instead of fruits, while in case of women not. Besides, there was a separate analysis and constraint on blue water footprint, it was not applied as a priority factor in the objective function, it was limited not to exceed the observed level. Again, as follows from the fact that female scenarios have lower energy content and lower quantity of food consumption, in the case of water-footprint reduced, nutritionally adequate, and cultural-acceptability-focused optimized, diets, there was more binding nutrient identified to be at risk in case of a dietary shift towards the water footprint-reduced, healthier diets.

6.5. Methodological considerations

6.5.1. Dietary scenarios analysis versus diet optimization

As introduced in section 3.8.1., sustainable dietary scenario analysis and diet optimization have a profoundly opposite logic. Based on S_3 and S_4, some methodological considerations can be concluded. The dietary scenario analysis, assessing the health and environmental impact of pre-designed scenarios can show a broad picture of the recommended and alternative diets planned according to criteria. As such, it can give a general and comprehensive picture of the pros and contras of these formal diets, however, since the dietary scenarios are pre-designed and the effects are post-analyzed, it is more difficult to get an exact solution for concrete problems. On the other hand, die optimization is an efficient tool for solving exact and well defend problems (e.g. to minimize the water footprint of diets), all desired aspects (e.g. nutritional quality, environmental impact) can be controlled by constraints or the objective function (Gazan, Brouzes et al., 2018; van Dooren, 2018). As follows from its, diet optimization is a more adequate tool to ensure cultural acceptability since the minimal deviation from the observed diet can be prioritized as the objective function and there is no need for the pre-exclusion of whole food groups. In summary, dietary scenario analysis is more like an exploratory method that can provide a broad picture of the desired direction in changing diet and evaluation about recommended and alternative diets, while diet optimization is an effective tool to solve concrete diet problems.

6.5.2. Aspects for in-depth analysis of sustainable nutrition

The optimal solution for dietary water footprint reduction (with the respect to dietary quality and cultural acceptability) lies in the in-depth analyses of observed and optimized diets and scenarios. The following aspect should especially be considered in the design of the study and analysis of results:

(1) Cultural acceptability: cultural acceptability is often disregarded in the case of pre-designed vegan or vegetarian dietary scenarios, as well as by the exclusion of whole food groups. A huge shift from the observed diets would violate cultural acceptability and would not necessarily lead to more sustainable diets (Vieux et al., 2020). Furthermore, cultural acceptability is a not yet defined term nor can be quantified, thus the aim could only be "as close as possible" to the observed diet. The measure of dietary change could provide an objective picture to analyse this aspect (see section 3.3.1.).

(2) Effects of food group replacement. The replacement of food groups may lead to expected and not expected health or environmental effect that should be considered, besides the huge change in diet that lower cultural acceptability. For example, S_3 showed that the replacement of meats for milk and dairies and eggs would lead to no considerable benefit nor in dietary quality neither in dietary water footprint. Furthermore, the replacement of animal-based foods can pose a considerable risk for micronutrient deficiency (S4), (BDA, 2018; Gazan, Brouzes et al., 2018; Perignon et al., 2016a; Scarborough et al., 2012).

(3) Included and excluded solid and liquid food groups. The inclusion or exclusion of food groups should be well presented and implemented in the interpretation of results. Also, a clear description

of food group classification, datatypes, and data aggregation should be included in the studies. Furthermore, the inclusion of drinks – especially fruit juices, coffee, tea and alcohol in the analysis can lead to a huge difference in the environmental impact (Lares-Michel et al., 2021)., thus included or not, it should be considered when analysing the results.

(4) Detailed analyses of food sub-groups among main food groups. As S_4, showed a detailed analysis of the food sub-group can reveal important details about the diets towards more sustainable diets (Lluch et al., 2017). For example, even though meats and dairies are the greatest contributors to the dietary water footprint on the population-level, the increased intake of poultry and fermented dairies can still be a way to change diet. Often, data is processed on a subgroups level, but results are only shown on the main food group level leaving out important details (Hallström et al., 2015; Harris et al., 2020; Jones et al., 2016; Steenson & Buttriss, 2021; Vettori et al., 2021). Furthermore, considering average values on the main food groups level can cover the effect of the outstandingly low or high values of food sub-groups items: beef in the meat food groups, legumes in the vegetable food group, and nut and fruits juices in the fruits food groups.

(5) Type of included water footprint in the analyses. Traditionally, only blue water footprint (or freshwater use) was considered in sustainable studies, but this paradigm changed, and the inclusion of green and grey water footprints are suggested (Falkenmark & Rockström, 2006; Harris et al., 2020; Hoekstra, 2015; Hoff et al., 2010; Vanham, 2020). That makes it difficult to compare different studies. Blue water footprint has usually shown a different trend towards more sustainable diets than other metrics such as green water footprint, land use, or GHGE (Chaudhary & Krishna, 2019; Hess et al., 2015; Springmann et al., 2018; Steenson & Buttriss, 2021; Tepper et al., 2022; Tom et al., 2016). That is most likely because of the high blue water footprint values of fruits, especially nuts that are otherwise beneficial in sustainable diets (Vanham et al., 2020). Due to this, the separate analysis of blue water footprint would be informative, because its effect may be covered if more environmental impact metrics are considered. Consequently, in the case of water footprint, the consideration of all elements is recommended (green, blue, grey) but conducting separate analyses on them can give clearer results (Ansorge & Stejskalová, 2022).

(6) Environmental impact indicators. Based on the holistic definition of more sustainable diets, there are a great number of metrics, including the several environmental impact factors included, so the future way would be to include them all and find the "golden middle way"(Gustafson et al., 2016; Vanham et al., 2019). However, the inclusion of numerous environmental metrics can cover

each other's effects (Vanham et al., 2020). Studies are designed by a specific or complex approach, and the interpretation of results should include limitations of both.

(7) Differences between sexes. As follows from the fact that men and women have different consumption patterns and nutrient requirements, analyses and results presented by sexes can reveal important details on differences (Meier & Christen, 2012); for example, as S_3 and S_4 also showed, different dietary shift and micro-nutrient deficiency risk towards the more sustainable diets.

7. LIMITATIONS

(1) Dietary data. The analyses are based on secondary data except in the case of S_3 the sample is not representative nor consists of a big number but was enough for calculating significance level. However, S_1 is based on a representative household survey about food consumption, and S_3 and S_4 are based on a representative dietary survey (section 4.2.1.)

(2) Sustainability metrics. In case when the quality database was available, the data is national specific, however, there is not yet a comprehensive and updated national database of food nutrient composition, thus the USDA FNDDS was applied (USDA, 2018). In the case when a specification of comparison was the aim, the global (WHO) and European (EFSA) RDIs were also used. Also, the calculation of food/diet nutrition composition is not corrected with bio-availability factors. Furthermore, since in the USDA FNDDS added sugars content is not included it was estimated otherwise or excluded from the analyses.

(3) In S_4, in the estimation of the observed diet, the “other foods” (277 g/day/capita) sub-group was excluded, since it was mostly composed of ultra-processed foods (e.g., soup powder) impossible to aggregate and compile due to their heterogeneity and intake level, which was generally under 1 g/day/capita. Furthermore, the estimation of their food-related water footprint would be a great methodological difficulty since the database mainly consists of food with lower processing levels (Mekonnen & Hoekstra, 2010a, 2010b).

(4) In S3, scenarios are “theoretical” diets that are based on the current nutrition pattern of Hungary. In studies that analyse dietary scenarios, there is always a question as to how realistic they are. “Cultural acceptability” is a very important aspect of sustainable nutrition and even though dietary quality and sustainability are crucially important for the next generations, we cannot map out a pathway for future nutrition that is not regionally acceptable. In this study, cultural acceptability was ensured with the food items included all of which were the most commonly consumed food items weighted by their supply value according to our national statistical data.

(5) Environmental impact factors. As based on the "specific" approach, the dissertation only includes analyses of water footprint. As it has previously been proven and also the conclusion of this dissertation, different than water footprint factors could also result in a different effect on the healthiness–environment synergies. On the other hand, a separate, more detailed analysis could reveal important details to consider about a sole member of the footprint family that could be covered in a multifactorial and less context-specific analysis. However, the dissertation (S_1, S_3, S_4) included separate considerations of blue and

green water footprints. Nevertheless, a further aim could be to find the agreement between the different footprints.

(6) Comparison with other, similar studies. The comparison with other studies is difficult due to different methodologies affecting every phase of the study: dietary data included metrics, bottom-up or top-down estimation footprints, scenario analysis or optimization, parameters of the diet optimization model, or the focused population. However, most studies on the dietary water footprint apply the database of WFN, which is country-specific and comparable (Mekonnen & Hoekstra, 2010a, 2010b)

(7) The estimation for observed dietary water footprint was carried out in the major studies: total, green and blue in the work of S_4, and green and blue in S_3. The result showed differences due to methodological consideration: in the dietary scenarios analyses (S_3) the values were lower (SM Table 9.) because: (1) only solid foods were considered (except alcohols) that especially because fruit juices – resulted in lower total water footprint, (2) the high water footprint value of legumes among vegetables and nut among fruits were covered in the weighted average of the main groups, (3) the data source was the same, but in different dimensions: S_4 was based on the estimated intake of food in g/d/c while in S_3 it was based on kcal/d/c. Considering that S_4 estimated total dietary water footprint data and a wider range of food groups and sub-groups, I considered its results of it more accurate.

8. SUMMARY

Introduction: The depletion of natural resources, peeking global population, and climate change all point toward one of the most challenging problems for humanity in the nearby future. To address this problem, the United Nations defined the Sustainable Development Goals, among which there are numerous aims at a sustainable food system and nutrition (United Nations, 2015). One of the approaches to release this global burden is the concept of sustainable nutrition that, by definition, includes holistic elements besides human health: economic, socio-cultural, and environmental dimensions (FAO and WHO, 2019; Fischer & Garnett, 2016). To realize the complex concept of sustainable nutrition, dietary or food-related environmental impact, health, socio-cultural and economic aspects have been put into the focus of research in this field. To study its comprehensive approach to sustainable nutrition, three main methodological approaches has been developed: (1) descriptive and correlative analyses between the metrics of sustainable nutrition, (2) dietary-scenarios analysis: the comparison of baseline and alternative dietary scenarios and their impact, (3) sustainable diet optimization (Hallström et al., 2015; Hallström et al., 2016; Jones et al., 2016; Perignon et al., 2016a; Gazan, Brouzes et al., 2018; van Dooren, 2018; Harris et al., 2020; Vettori et al., 2021). This dissertation focuses on food-related and dietary water footprint as environmental impact indicators, besides nutritional or dietary quality and cultural acceptability adapted at the Hungary population-level. The water footprint is of special importance since 70% of the total anthropogenic footprint is created by food production, besides, it is the main course of water pollution (FAO and WHO, 2019). Besides, in its latest country-specific recommendation, the EC urges Hungary to implement reforms and investments in sustainable water management (EC, 2022b). Furthermore, dietary risk factors are the second largest (after tobacco use) contributors to the development of Noncommunicable diseases (NCDs), which are the leading cause of death in the developed countries (IHM, 2019), thus a shift toward more sustainable diets would also be critically important regarding the issue of health, however, this dietary shift should also regard cultural acceptability.

Aims: The aims of this research are threefold: (1) applying the state-of-the-art methods, to analyse and optimize the nutritional/dietary quality and food-related/dietary water footprint and their associations on the Hungarian population-level regarding its cultural aspects, (2) to provide evidence-based methods and information to nutritionist practitioners for the inclusion of dietary water footprint aspect in their counseling practice, and (3) to provide supporting evidence for the development of national FBDGs from the aspect of dietary water footprint. The aims were realized in 4 different studies (S_1-S_4) and in their fused conclusions.

Methods: **(S_1)** Association of food-related water footprint and nutrient composition of the most consumed foods and food categories. The study design consists of the correlation analysis between the nutrient composition and green and blue water footprint of the most commonly consumed food items in Hungary (n = 44) and the classification of nutrients based on their association with food-related blue and green water footprint and population intake level. **(S_2)** Association of dietary water footprint and dietary quality of individual diets – an integrative and statistical analysis. The study design included the common measurement of a nutritionist practice: diet analysis based on 3-day dietary records and body composition measurement with the addition of dietary water footprint analysis of diets (n = 25). It was aimed to identify the association between dietary quality, body composition – as health indicators – and the environmental impact of diets, besides, to identify sustainable dietary factors based on descriptive and correlative analyses. **(S_3)** Water footprint and dietary quality consequences of alternative diets – dietary scenarios analysis. The main concept of the study design was to evaluate the dietary quality (i.e. health) and the blue and green dietary water footprint impact of different dietary scenarios based on the observed population diet and its alternative scenarios. In this comprehensive work, blue and green dietary water footprint assessment and 2 types of dietary quality scores and their integrative score value was developed to evaluate the dietary quality of 6 different dietary scenarios: baseline, reduced meat, vegetarian, vegan, sustainable, cardio protective and ketogenic. **(S_4)** The design of the diet optimization model targets water footprint reduction while fulfilling nutritional adequacy and respecting cultural acceptability. A linear programming-based diet optimization model was designed to target stepwise dietary water footprint reduction while fulfilling nutritional adequacy and minimizing deviation from the typical population observed diet.

Results: **(S_1)** Based on the blue and green water footprint and nutrient composition of the most consumed foods and food categories as variables, Spearman rank-correlation proved association in several cases ($p < 0.05$). Notably, there was a significant positive correlation found between the following nutrient composition and food-related WFP of energy, total protein, cholesterol, total fats, SFA, riboflavin, and vitamin B_{12} among which, energy, total fats, SFA, cholesterol population intake is higher than recommended, hence foods with a high content of these nutrients should be limited in the water footprint friendly and healthier diets. On the other hand, a negative significant correlation was proved in the case of total carbohydrates, dietary fibers, folic acid, and vitamin C among which the population intake of total carbohydrates, dietary fibers, and folic acid are lower than recommended, thus the foods with high content of these nutrients should be promoted in water footprint friendly, healthier diets. Protein was found as an important indicator in a positive significant relationship with water footprint, however, the population intake is adequate, hence the source of intake should be considered: more animal-based and less plant-based foods. **(S_2)** By analysing 25 individual diets and body composition, spearman correlation analysis (p < 0.0.5) proved a positive significant association between total dietary WFP and energy, SFA, protein, sodium, and total meat intake, while negative significant relationship between total dietary WFP and DQS, DQS also showed negative significant association with meat intake. There was no significant correlation between body composition and other variables. These results suggest that dietary intervention in nutritionist practice (lower met consumption, more diverse protein sources, lowering the non-beneficial nutrients (i.e. sodium, SFA), elevating the beneficial nutrients (i.e. dietary fibers)) could have a double benefit: water-footprint friendly and healthier. **(S_3)** Based on the health and water footprint impact assessment of baseline and alternative dietary scenarios on the population-level, the "sustainable scenario" was identified as the most beneficial in these aspects (+9% in dietary quality, −41.7% in green water footprint, and −28.9% in blue water footprint) compared to the observed dietary scenarios on average of both sexes. In comparison with the observed diets in the population, it is characterized by more diverse intake sources of proteins, lower intake of meats and milk and diaries, and higher intake of plant-based proteins, vegetables and fruits, and similar grains, fats, and oils content. **(S_4)** Diet optimization designed to be nutritionally adequate, cultural acceptability-focused and water footprint reduced resulted in a ~ 23.9 % water footprint reduction for both sexes besides providing nutritional adequacy and respecting cultural acceptability (~ 32% dietary shift). The observed total dietary water footprint was 3484 l/d/c (both sexes), and its main contributors were the followings: milk and dairies (1088.1 l/d/c) and meats and meat products (984.2 l/d/c) contributed the most to the total dietary water footprint, followed by grains (363.2 l/d/c) and fruits and products for (230,55 l/d/c). On the food sub-groups level milk and dairies (481.6 l/d/c), meat products (348.2 l/d/c), pork meat (294.0 l/d/c), cheese (284.3 l/d/c), and fresh and frozen fruits (202.8 l/d/c) were the main contributors. In the water footprint–healthiness synergy, the vegetables, eggs, poultries, and fermented dairies were the most beneficial, increasing in amount in the optimized diets, while fatty dairies, foods high in added sugar, and meat products were the most non-beneficial food sub-groups, decreasing in amount in the optimized diets. In the optimized diets minimum RDI of dietary fibers for both sexes, vitamin B-12, calcium, iron, zinc, and potassium for women, zinc and vitamin-D for men, while the maximum RDI of energy and sodium for both sexes, and total fat for men were identified as problematic nutrients, so they should be especially concerned in the case of a dietary shift towards water footprint friendly and healthier diets.

Conclusions and recommendations: The conclusions are valid for (1) food related/dietary water footprint, (2) nutritional/dietary quality and (3) cultural acceptability among the sustainable nutrition dimensions, besides, they are representative for the Hungarian population.

The observed total dietary water footprint was 3484 l/day/capita (green: 3039 l/day/capita and blue: 70.2 l/day/capita) among the Hungarian population averaged for the two sexes. The proportion of green dietary water footprint makes the majority up of total (86-87%) and the proportion of blue water footprint is (2-3%) that is typical for this geographical region and require special considerations due to the climate change and its effect on water-management With a well-designed sustainable diet optimization considerable reduction is possible from total dietary water footprint (~23.9%), while nutritionally adequate and cultural-acceptability-focused the diets are, without the pre-exclusion of animal-based foods. The dietary blue water footprint should be analyzed and interpreted separately given its significant importance and different impact from other environmental impact categories, including green water. The main dietary water footprint contributors of the observed diets are the milk and dairies and meats, however, the quality change (preference for low fat and low processed products over high fat and highly processed products) of them would be just as important as the total quantity change in the main food group intake. More water footprint-friendly and healthier diets that respect the traditional dietary patterns could be described the simplest as "reduced animal-based foods” diets, especially reduced in highly processed and high fat meats and dairies, however, without the elimination of main food groups. Besides, it contains an elevated amount of vegetables and grains, while among fruits and products, the fresh and non-processed ones should be preferred over high processed products and added sugar content, since they heavily impact the dietary blue water footprint. The source of protein could be a key factor in the water footprint friendly and healthier diets since it strongly correlates with water footprint (in plant-based food also) but the population intake is adequate: the more diverse (including less animal- and more plant-based foods) source of the intake the better, while over-consumption should be avoided. Besides, energy, saturated fatty acids, dietary fibers, calcium, vitamin-B_{12}, vitamin-C, sodium, vitamin-D, iron, zinc, and potassium were identified as problematic nutrients to reach minimum adequate intake or not exceed the maximum recommended intake value when dietary water-footprint reduction is targeted, and nutritional adequacy should be ensured on the population-level.

9. ÖSSZEFOGLALÁS

Bevezetés. A természeti erőforrások kimerülése, a világ népességének növekedése és a klímaváltozás együttesen az egyik legnagyobb kihívást jelentik a közeljövőben az emberiség számára. E probléma megoldására az Egyesült Nemzetek Szervezete meghatározta az ún. Fenntartható Fejlődési Célokat, amelyek között a fenntartható élelmiszerláncra és táplálkozásra (United Nations, 2015) vonatkozóan több cél is szerepel. A globális, fenntartható fejlődést érintő feladatok egyike a fenntartható táplálkozás kialakítása. Ennek során az az emberi egészség mellett gazdasági, társadalmi-kulturális és környezeti tényezőket is figyelembe kell venni. (Fischer & Garnett, 2016; FAO and WHO, 2019). Ebből adódóan fenntartható táplálkozás komplex koncepciójának megvalósítása érdekében az étrenddel vagy élelmiszerekkel kapcsolatos környezeti hatások, egészségi, társadalmi-kulturális és gazdasági szempontok kerültek a kutatások fókuszába. A fenntartható táplálkozás átfogó megközelítésének tanulmányozására három fő módszertani megközelítést dolgoztak ki: (1) leíró elemzések és összefüggésvizsgálat a fenntartható táplálkozás indikátorai között, (2) étrendi szcenáriók elemzése: alap (lakosság aktuális táplálkozási mintázata) és alternatív étrendi forgatókönyvek és környezetterhelésre gyakorolt hatásuk összehasonlítása, (3) táplálkozás optimalizálása fenntarthatósági céloknak megfelelően (Hallström et al. 2015; Hallström et al., 2018; Jones et al., 2016; Perignon et al., 2016a; Gazan, Brouzes et al., 2018; van Dooren, 2018; Harris et al., 2020; Vettori et al., 2021). A jelen disszertáció célja, hogy megvizsgálja a vízlábnyom csökkentésének lehetőségeit az élelmiszer-fogyasztás mintázatainak módosításával, mert kiemelt jelentősége van; a teljes antropogén lábnyom 70%-át az élelmiszertermelés teszi ki, emellett ez a vízszennyezés fő oka (FAO and WHO, 2019). Emellett, a legfrissebb, országspecifikus ajánlásában az Európai Bizottság felhívja a figyelmet a fenntartható víz-menedzsmenttel kapcsolatos intézkedések fontosságára (EC, 2022b). Továbbá, az étrendi kockázati tényezők (mint rizikófaktorok) járulnak hozzá a második legnagyobb mértékben (a dohányzás után) a krónikus, nem fertőző betegségek (NCD-k) kialakulásához, amelyek a fejlett országokban a vezető halálokokat adják (IHM, 2019). A fenntartható(bb) táplálkozás felé történő változtatások az egészség szempontjából is kritikus fontosságúak, azonban ennek a táplálkozásban bekövetkezett változásnak a kulturális elfogadhatóságra is tekintettel kell lennie, mert az élelmiszerekhez köthető szokások és preferenciák kulcsfontosságúak a témában.

Célok. A kutatásnak három fő célja volt: (1) a legkorszerűbb módszerek alkalmazásával elemezni és optimalizálni az étrendminőséget, az élelmiszerekkel kapcsolatos/étrendi vízlábnyomot és ezek összefüggéseit a magyar lakosságra vonatkozóan a kulturális sajátosságokat figyelembe véve, (2) bizonyítékokon alapuló módszereket és információkat nyújtani a táplálkozástudományi szakembereknek azért, hogy az étrendi vízlábnyom aspektusát be tudják építeni tanácsadói gyakorlatukba, és (3) a nemzeti élelmiszer-alapú táplálkozási ajánlások kidolgozásához további tudományos bizonyítékot nyújtani az étrendi vízlábnyom vonatkozásában. E három célkitűzés 4 különböző tanulmányban (S1-S4) került megvalósításra, amelyek együttesen adták a következtetések alapját.

Módszertan. (S$_1$) A kutatás célja az élelmiszerekhez köthető vízlábnyom és tápanyag-összetétel közötti összefüggés vizsgálata volt a leggyakrabban fogyasztott élelmiszerek és élelmiszerkategóriák vonatkozásában. A kutatás a Magyarországon leggyakrabban fogyasztott élelmiszerek (n = 44) tápanyag-összetétele és zöld- és kékvízlábnyoma közötti korrelációs elemzésből állt. Ezen eredményekre alapozva sor került a tápanyagok klasszifikációjára az élelmiszerekhez köthető kék- és zöldvízlábnyommal való összefüggésük és a tápanyagok lakossági beviteli szintje alapján. **(S$_2$)** A kutatás célja az étrendi vízlábnyom és egyéni étrendek étrendminőségének összefüggésvizsgálata volt integratív megközelítésben. A kutatás magában foglalta a táplálkozási felmérések során alkalmazott táplálkozástudományi gyakorlatokat: 3 napos táplálkozási naplón alapuló étrend-elemzés, testösszetétel-mérés, az egyéni étrendek étrendi vízlábnyom-elemzése valósult meg (n=25). Célom volt az étrendminőség, a testösszetétel – mint egészségi indikátorok – és az étrendek környezeti hatása közötti összefüggések elemzése, valamint a fenntartható étrendi tényezők azonosítása leíró és korreláció elemzések alapján. **(S$_3$)** Alternatív étrendek vízlábnyomának és étrendminőségének vizsgálata – étrendi szcenáriók elemzése. A kutatás fő célja az volt, hogy értékelje a különböző étrendi szcenáriók étrendminőséget (tehát egészségességét), valamint a kék és zöld étrendi vízlábnyomot értinő hatását. Ebben az átfogó munkában kétféle étrendminőségi pontértéket és ezek integrált értékét dolgoztam ki az étrendminőség értékelésére 6 különböző étrendi szcenárióban: kiindulási (magyar lakosság aktuális táplálkozási mintázata), csökkentett hústartalmú, vegetáriánus, vegán, fenntartható, kardioprotektív és ketogén étrend. **(S$_4$)** A kutatás célja étrendoptimalizáló modell kidolgozása volt, amely a vízlábnyom csökkentését célozta meg, és egyúttal megfelel a táplálkozásélettani kritériumoknak, továbbá a kulturális elfogadhatóságot is figyelembe vette. A lineáris programozáson alapuló modellben az étrendi vízlábnyom fokozatos/lépcsőzetes csökkentése történt, a tápanyagbeviteli korlátoknak megfelelően, és minimálisra csökkentve a populáció megfigyelt étrendjétől való eltérést, mint célfüggvény.

Eredmények. (S$_1$) A Magyarországon leggyakrabban fogyasztott élelmiszerek kék és zöld vízlábnyom értékei és tápanyag-összetétele (mint változók) között a Spearman-féle rangkorreláció alapján több esetben is összefüggés volt igazolható ($p < 0{,}05$). Figyelemre méltó, hogy szignifikáns pozitív korrelációt találtam a következő tápanyagok és az élelmiszerekhez köthető vízlábnyom között: energia, összes fehérje, koleszterin, összes zsír, SFA, riboflavin és B12-vitamin. Ezen tápanyagok közül az energia, az összes zsír, az SFA, és a koleszterin bevitele populációs szinten magasabb az ajánlottnál, ezért ezekben a tápanyagokban gazdag élelmiszerek fogyasztása korlátozásra javasolt a csökkentett vízlábnyomú és egészségesebb étrendekben. Ezzel szemben az összes szénhidrát, élelmi rost, folsav és C-vitamin esetében negatív szignifikáns korreláció igazolódott, amely tápanyagok közül a lakosság összes szénhidrát, élelmi rost és folsav bevitele alacsonyabb az ajánlottnál. Így ezen tápanyagokban gazdag élelmiszerek fogyasztását a csökkentett vízlábnyomú és egészségesebb étrendben célszerű növeli. A fehérje fontos indikátornak mutatkozott pozitív szignifikáns összefüggésben a vízlábnyommal, azonban a lakosság fehérjebevitele megfelelő, ezért a bevitel forrását érdemes mérlegelni: kevesebb állati és több növényi eredetű élelmiszer fogyasztása javasolt. **(S$_2$)** A 25 egyén étrend és testösszetétel elemzése során a Spearman korrelációs analízis ($p < 0,05$) pozitív szignifikáns összefüggést mutatott ki a teljes étrendi vízlábnyom és az energia, az SFA, a fehérje, a nátrium és az összes húsbevitel között, míg negatív szignifikáns összefüggést mutatott ki a teljes étrendi vízlábnyom és az étrendminőség között. Az étrendminőség szintén negatív szignifikáns összefüggésben állt a húsfogyasztással. A testösszetétel és más változók között nem volt szignifikáns korreláció. Ezek az eredmények azt sugallják, hogy az étrendi intervenciók szerepének (kisebb húsfogyasztás, változatosabb fehérjeforrások, a nem előnyös tápanyagok csökkentése, az előnyös tápanyagok mennyiségének növelése) a táplálkozási tanácsadás gyakorlatában kettős előnye lehet: csökkentett vízlábnyomú és egészségesebb táplálkozás felé történő elmozdulás elősegítése. **(S$_3$)** Az alap- és alternatív étrendi szcenáriók lakossági szintű egészségügyi és vízlábnyom-hatásvizsgálata alapján a „fenntartható szcenárió” volt a legelőnyösebb (+9% az étrendminőségben, 41,7% a zöld vízlábnyomban, és 28,9% a kék vízlábnyomban) az alap szcenáriókhoz képest mindkét nem átlagában. A populációban megfigyelt étrendekhez képest a fenntartható szcenárióban változatosabb a fehérjeforrások bevitele, kisebb hús és tej- és tejtermékbevitel, nagyobb növényi eredetű fehérje, zöldség- és gyümölcsbevitel, továbbá hasonló mértékű gabona-, zsír- és olajbevitel alapján jellemezhető. **(S$_4$)** A táplálkozás-élettani korlátoknak megfelelő, kulturális elfogadhatóság-központú és a vízlábnyom csökkentését célzó étrend-optimalizáló modell 23,9%-kal kisebb étrendi vízlábnyomot eredményezett mindkét nem átlagában 32%-os étrendi változás mellett. A megfigyelt teljes étrendi vízlábnyom 3484 l/fő/nap (mindkét nemnél) volt, amihez a tej és tejtermékek (1088,1 l/fő/nap), valamint a húsok és húskészítmények (984,2 l/fő/nap) járultak hozzá a legnagyobb mértékben, ezt követik a gabonafélék (363,2 l/fő/nap) a gyümölcsök és gyümölcskészítmények (230,55 l/fő/nap). Az élelmiszer-alcsoportok szintjén a tej és tejtermékek (481,6 l/fő/nap), húskészítmények (348,2 l/fő/nap), sertéshús (294,0 l/fő/nap), sajt (284,3) l/fő/nap), illetve a friss és fagyasztott gyümölcsök (202,8 l/fő/nap) járultak hozzá főként az étrendi vízlábnyomhoz. A vízlábnyom-egészség szinergiában a zöldségek, a tojás, a baromfihús és az erjesztett tejtermékek voltak a legelőnyösebbek, mennyiségük növekedett az optimalizált étrendekben, míg a nagy zsírtartalmú tejtermékek, a magas hozzáadott cukortartalmú élelmiszerek és a húskészítmények előnytelen élelmiszer-alcsoportok, mennyiségük csökkent az optimalizált étrendekben. Az optimalizált étrendben az élelmi rostok minimális RDI-értéke mindkét nemnél kritikus tápanyagként jelent meg, emellett a nőknél a B-12-vitamin, a kalcium, a vas, a cink és a kálium, míg a férfiaknál a cink és a D-vitamin jelent meg kritikus tápanyagként. Az energia és a nátrium maximális RDI-értéke mindkét nemnél, valamint a férfiaknál a teljes zsírtartalmat azonosítottam problémás tápanyagként, ezért ezeknél a tápanyagoknál különös figyelmet kell fordítani a csökkentett vízlábnyomú és egészségesebb étrend felé történő elmozdulás esetén.

Következtetések és javaslatok. A következtetések érvényesek a (1) élelmiszerhez köthető/étrendi vízlábnyomra, (2) tápanyag/étrendminőségre és a (3) kulturális elfogadhatóságra a fenntartható táplálkozás dimenziói között, emellett reprezentatívak a magyar populációra nézve.

A megfigyelt összes étrendi vízlábnyom 3484 l/nap/fő (zöld: 3039 l/nap/fő, kék: 70.2 l/nap/fő) volt a magyar populációra értve a két nem átlagos értékeit figyelembe véve. A zöld vízlábnyom aránya tette ki az összes érték nagy többségét (86-87%), míg a kék a 2-3%-át, ez jellemző erre a földrajzi régióra és különös megfontolást igényel a klímaváltozás víz-menedzsmentre várható hatása miatt. Egy jól megtervezett, fenntartható étrend-optimalizáló modell kidolgozásával a teljes étrendi vízlábnyom jelentős csökkentése lehetséges (~23,9%), a táplálkozási-élettani kritérium kielégítése és kulturális-elfogadhatóság megőrzése mellett, illetve az állati eredetű élelmiszerek előzetes csökkentése vagy kizárása nélkül. Az étrendi kék vízlábnyom elemzése és értelmezése külön javasolt a többi környezeti hatás indikátortól (beleértve a zöld vízlábnyomot is) eltérő hatása miatt. A megfigyelt étrendi vízlábnyomhoz a tej és tejtermékek, valamint a húsok és húskészítmények járulnak hozzá a legnagyobb mértékben, azonban ezen élelmiszercsoportoknak a minőségi változtatása (az alacsony zsírtartalmú és feldolgozottságú termékek előnyben részesítése a magas zsírtartalmú és feldolgozottságú termékekkel szemben) ugyanolyan fontos lenne, mint az összes beviteli mennyiség. A csökkentett vízlábnyomú és egészségesebb, a hagyományos táplálkozási mintázatot tiszteletben tartó étrendek legegyszerűbben „csökkentett állati eredetű élelmiszereket tartalmazó” étrendként írhatók le, különösen a feldolgozott és nagy zsírtartalmú hús- és tejtermékek csökkentésével, azonban a fő élelmiszercsoportok kizárása nélkül. Emellett ezen étrendek nagyobb mennyiségű zöldséget, gabonát tartalmaznak, míg a gyümölcsök és a gyümölcskészítmények közül a friss és a feldolgozatlan formát érdemes előnyben részesíteni a magas feldolgozottsági fokú, hozzáadott cukortartalmú termékekkel szemben, mivel ezek nagymértékben befolyásolják az étrendi kékvízlábnyomot. A fehérjeforrások kulcsfontosságú tényezők lehetnek a csökkentett vízlábnyomú és egészségesebb táplálkozásban, hiszen a fehérjetartalom erősen korrelál a vízlábnyommal (növényi alapú élelmiszereknél is). A lakosság fehérjebevitele megfelelő, ezért minél változatosabb fehérjeforrások választása célszerű, míg a túlzott fehérjebevitelt kerülni kell. Emellett az energiát, telített zsírsavakat, az élelmi rostokat, a kalciumot, a B12-vitamint, a C-vitamint, a nátriumot, a D-vitamint, a vasat, a cinket, és a káliumot olyan potenciális problémás tápanyagnak tekinthető a lakossági bevitel szintjén, amelyet javasolt figyelembe venni, amikor az étrendi vízlábnyom csökkentése a cél a táplálkozás-élettani feltételek biztosítása mellett.

10. APPENDICIES

10.1. References

1. Adam-Perrot, A., Clifton, P., & Brouns, F. (2006). Low-carbohydrate diets: Nutritional and physiological aspects. *Obesity Reviews, 7*(1), 49–58. https://doi.org/10.1111/j.1467-789X.2006.00222.x
2. Alessandra, D. M. (2014). The Adherence of the Diet to Mediterranean Principle and Its Impacts on Human and Environmental Health. *International Journal of Environmental Protection and Policy, 2*(2), 64-75.
3. Ansorge, L. & Stejskalová, L. (2022). Water Footprint as a Tool for Selection of Alternatives (Comments on “ Food Recommendations for Reducing Water Footprint ”). *Sustainability, 14,* 6317. https:// doi.org/10.3390/su14106317
4. BCFN, Barilla Center for Food & Nutrition. (2016a). *Doppia Piramide, Database Tecnico [Double Pyramid, Tech. Paper]*. Available at: https://www.fondazionebarilla.com/publications/doppia-piramide-2016-un-futuro-piu-sostenibile-dipende-da-noi/ (last accessed: 02.03.2022.)
5. BCFN, Barilla Center for Food and Nutrition. (2016b). *DOPPIA PIRAMIDE, Un futuro più sostenibile dipende da noi* [*DOUBLE PYRAMID 2016, a more sustaible future depends on us]*. 71. Available at: https://www.fondazionebarilla.com/wp-content/uploads/2022/05/Doppia-Piramide-2016-Un-futuro-piu%CC%80-sostenibile-dipende-da-noi.pdf (last accessed:02.:06:2022.)
6. BDA, The Association of UK Dietitians. (2018). *OBD: Eating patterns for health and environmental sustainability.* British Dietetics Association, 1–91. Available at: https://www.bda.uk.com/uploads/assets/539e2268-7991-4d24-b9ee867c1b2808fc/421de049-2c41-4d85-934f0a2f6362cc4a/one%20blue%20dot%20reference%20guide.pdf (last accessed: 02.06.2022.)
7. Berkelaar, M. (2020). *Package lpSolve, R programming*. Available at: https://cran.r-project.org/web/packages/lpSolve/lpSolve.pdf (last accessed: 02.06.2022)
8. Capone, R., Iannetta, M., Bilali, H. el, Colonna, N., Debs, P., Dernini, S., … Belsanti, V. (2013). A Preliminary Assessment of the Environmental Sustainability of the Current Italian Dietary Pattern: Water Footprint Related to Food Consumption. *Journal of Food and Nutrition Research, 1*(4), 59–67. https://doi.org/10.12691/jfnr-1-4-5
9. Chaudhary, A., & Krishna, V. (2019). Country-specific sustainable diets using optimization algorithm. *Environmental Science and Technology*, *53*(13), 7694–7703. https://doi.org/10.1021/acs.est.8b06923
10. Chen, C., Chaudhary, A., & Mathys, A. (2019). Dietary change scenarios and implications for environmental, nutrition, human health and economic dimensions of food sustainability. *Nutrients*, *11*(4), 1–21. https://doi.org/10.3390/nu11040856
11. Cleveland, L. E., Escobar, A. J., Lutz, S. M., & Welsh, S. O. (1993). Method for identifying differences between existing food intake patterns and patterns that meet nutrition recommendations. *Journal of the American Dietetic Association, 93*(5), 556–563. https://doi.org/10.1016/0002-8223(93)91816-9
12. CSO, Central Statistical Office. (2018). Retrieved from Central statistic Office: Amount of Food Consumption per Capita per Year Classified by Income and Type of Region into Deciles 2018. website: https://www.ksh.hu/docs/hun/xstadat/xstadat_eves/i_zhc023a.html (last accessed: 02.06.2022.)

13. Darmon, N., Ferguson, E., & Briend, A. (2003). Do economic constraints encourage the selection of energy dense diets? *Appetite*, *41*(3), 315–322. https://doi.org/10.1016/S0195-6663(03)00113-2
14. Darmon, N., Vieux, F., Maillot, M., Volatier, J., & Martin, A. (2009). Nutrient profiles discriminate between foods according to their contribution to nutritionally adequate diets: a validation study using linear programming and the SAIN, LIM system. *American Journal of Clinical Nutrition, 89*(4), 1227–36 https://doi.org/10.3945/ajcn.2008.26465.
15. Dave, L. A., Suzanne M., Hodgkinson, M., Roy, N. C., Smith, N. W. & Mcnabb, W. C. (2021). The role of holistic nutritional properties of diets in the assessment of food system and dietary sustainability. *Critical Reviews in Food Science and Nutrition*, *0*(0), 1–21. https://doi.org/10.1080/10408398.2021.2012753
16. Downs, S. M., & Fanzo, J. (2015). Is a Cardio-Protective Diet Sustainable? A Review of the Synergies and Tensions Between Foods That Promote the Health of the Heart and the Planet. *Current Nutrition Reports*, *4*(4), 313–322. https://doi.org/10.1007/s13668-015-0142-6
17. Drewnowski, A., Rehm, C. D., Martin, A., Verger, E. O., Voinnesson, M., & Imbert, P. (2015). Energy and nutrient density of foods in relation to their carbon footprint. *American Journal of Clinical Nutrition*, (July), 184–191. https://doi.org/10.3945/ajcn.114.092486
18. EC, European Commission. (2022a). *Food-Based Dietary Guidelines in Europe*. Summary of FBDG recommendations for meat for the EU, Iceland, Norway, Switzerland and the United Kingdom. Available at: https://knowledge4policy.ec.europa.eu/health-promotion-knowledge-gateway/food-based-dietary-guidelines-europe-table-8_en (last accessed: 02.06.2022.)
19. EC, European Commission. (2022b). *COUNCIL RECOMMENDATION on the 2022 National Reform Programme of Hungary and delivering a Council opinion on the 2022 Convergence Programme of Hungary* (Vol. 4). Available at: https://eur-lex.europa.eu/search.html?name=collection%3Aeu-law-pre-acts-com&type=named&qid=1653353289484&DD_YEAR=2022 (last accessed: 02.06.2022.)
20. EFSA, European Food Safety Authority. (2017). In *EFSA Supporting Publications, Dietary Reference Values for nutrients Summary report* (Vol. 14). https://doi.org/10.2903/sp.efsa.2017.e15121
21. Falkenmark, M., & Rockström, J. (2006). The New Blue and Green Water Paradigm: Breaking New Ground for Water Resources Planning and Management. *Journal of Water Resources Planning and Management*, *132*(3), 129–132. https://doi.org/10.1061/(asce)0733-9496(2006)132:3(129)
22. FAO and WHO., Food and Agricultural Organization of the United Nations and World Health Organization (2019). *Sustainable healthy diets – Guiding principles.* Roma, Available at: https://www.who.int/publications/i/item/9789241516648 (last accessed: 02.06.2022.)
23. FAO and WHO., Food and Agricultural Organization of the United Nations & World Health Organization. (2008). *Interim summary of conclusions and dietary recommendations on total fat and fatty acids. From the Joint FAO/WHO Expert Consultation on Fats and Fatty Acids in Human Nutrition*. Geneva. Available at: https://www.fao.org/ag/agn/nutrition/docs/fats%20and%20fatty%20acids%20summary.pdf (last accessed: 02.06.2022.)
24. FAO, Food and Agricultural Organization of the United Nations. (2020). Food Balance Sheet. Retrieved from Food and Agriculture Organization (FAO): Food Balance Sheet website: Available at: https://www.fao.org/faostat/en/#data/FBS (last accessed:02.06.2022.)

25. FAO. (2000). Food and Agricultural Organization of the United Nations. *Technical Conversion Factors for Agricultural Commodities. Food and Agriculture Organization of the United Nations*. Available at: http://www.fao.org/economic/the-statistics-division-ess/methodology/methodology-systems/technical-conversion-factors-for-agricultural-commodities/en/ (last accessed: 02.06.022.)
26. Fardet, A., & Rock, E. (2014). Toward a new philosophy of preventive nutrition: From a reductionist to a holistic paradigm to improve nutritional recommendations. *Advances in Nutrition*, *5*(4), 430–446. https://doi.org/10.3945/an.114.006122
27. Fehér Ferencné, Mák, E., Molnár Sz., Tóth T. & Vékony B. (2020). *Közétkeztetési szakácskönyv [Recipe book for school catering]* (Digital). Budapest: Akadémia kiadó. Available at: https://mersz.hu/hivatkozas/ksz_0#ksz_0 (last accessed: 02.06.2022.)
28. Fern, E. B., Watzke, H., Barclay, D. V., Roulin, A., & Drewnowski, A. (2015). The nutrient balance concept: A new quality metric for composite meals and diets. *PLoS ONE*, *10*(7), 1–18. https://doi.org/10.1371/journal.pone.0130491
29. Fernandez, M. L., Raheem, D., Ramos, F., Carrascosa, C., Saraiva, A., & Raposo, A. (2021). Highlights of current dietary guidelines in five continents. *International Journal of Environmental Research and Public Health*, *18*(6), 1–9. https://doi.org/10.3390/ijerph18062814
30. Fischer, C.G. and Garnett, T. (2016). *Plates, pyramids and planets: developments in national healthy and sustainable dietary guidelines: a state of play assessment*. FAO, Roma; FCRN, University of Oxford, Oxford. p. 71. Available at: http://www.fao.org/3/i5640e/I5640E.pdf (last accessed: 02.06.2022)
31. Gallo, I., Landro, N., Grassa, R. la, & Turconi, A. (2022). Food Recommendations for Reducing Water Footprint. *Sustainability. 14(*7), 3833; https://doi.org/10.3390/su14073833
32. Gazan, R., Barré, T., Perignon, M., Maillot, M., Darmon, N., & Vieux, F. (2018). A methodology to compile food metrics related to diet sustainability into a single food database: Application to the French case. *Food Chemistry, 238,* 125–133. https://doi.org/10.1016/j.foodchem.2016.11.083
33. Gazan, R., Brouzes C. MC., Vieux, F., Maillot, M., Lluch, A., & Darmon, N. (2018). Mathematical Optimization to Explore Tomorrow's Sustainable Diets: A Narrative Review. *Advances in Nutrition*, *9*(5), 602–616. https://doi.org/10.1093/advances/nmy049
34. Gephart, J. A., Davis, K. F., Emery, K. A., Leach, A. M., Galloway, J. N., & Pace, M. L. (2016). The environmental cost of subsistence: Optimizing diets to minimize footprints. *Science of the Total Environment*, *553*, 120–127. https://doi.org/10.1016/j.scitotenv.2016.02.050
35. Gibin, D., Simonetto, A., Zanini, B., & Gilioli, G. (2022). A framework assessing the footprints of food consumption. An application on water footprint in Europe. *Environmental Impact Assessment Review*, *93*(January), 106735. https://doi.org/10.1016/j.eiar.2022.106735
36. Gustafson, D., Gutman, A., Leet, W., Drewnowski, A., Fanzo, J., & Ingram, J. (2016). Seven food system metrics of sustainable nutrition security. *Sustainability (Switzerland), 8*(3), 1–17. https://doi.org/10.3390/su8030196
37. Hallström, E., Carlsson-Kanyama, A., & Börjesson, P. (2015). Environmental impact of dietary change: A systematic review. *Journal of Cleaner Production, 91*, 1–11. https://doi.org/10.1016/j.jclepro.2014.12.008

38. Hallström, E., Davis, J., Woodhouse, A., & Sonesson, U. (2018). Using dietary quality scores to assess sustainability of food products and human diets: A systematic review. *Ecological Indicators*, *93*(May), 219–230. https://doi.org/10.1016/j.ecolind.2018.04.071
39. Harris, F., Moss, C., Joy, E. J. M., Quinn, R., Scheelbeek, P. F. D., Dangour, A. D., & Green, R. (2020). The Water Footprint of Diets: A Global Systematic Review and Meta-analysis. *Advances in Nutrition*, *11*(2), 375–386. https://doi.org/10.1093/advances/nmz091
40. Hendrie, G. A., Baird, D., Ridoutt, B., Hadjikakou, M., & Noakes, M. (2016). Overconsumption of energy and excessive discretionary food intake inflates dietary greenhouse gas emissions in Australia. *Nutrients*, *8*(11). https://doi.org/10.3390/nu8110690
41. Hendrie, G. A., Ridoutt, B. G., Wiedmann, T. O., & Noakes, M. (2014). Greenhouse gas emissions and the Australian Diet-Comparing dietary recommendations with average intakes. *Nutrients*, *6*(1), 289–303. https://doi.org/10.3390/nu6010289
42. Hess, T., Andersson, U., Mena, C., & Williams, A. (2015). The impact of healthier dietary scenarios on the global blue water scarcity footprint of food consumption in the UK. *Food Policy*. *50* (2015) 1–10. https://doi.org/10.1016/j.foodpol.2014.10.013
43. Hoekstra, A. Y. (2015). The water footprint of industry. In *Assessing and Measuring Environmental Impact and Sustainability*. Elsevier Inc., Amsterdam. https://doi.org/10.1016/B978-0-12-799968-5.00007-5
44. Hoekstra, A. Y. (2017). Water Footprint Assessment: Evolvement of a New Research Field. *Water Resources Management*, *31*(10), 3061–3081. https://doi.org/10.1007/s11269-017-1618-5
45. Hoekstra, A. Y., & Wiedmann, T. O. (2014). Humanity's unsustainable environmental footprint. *Science*, Vol. 344, pp. 1114–1117. American Association for the Advancement of Science. https://doi.org/10.1126/science.1248365
46. Hoff, H., Falkenmark, M., Gerten, D., Gordon, L., Karlberg, L., & Rockström, J. (2010). Greening the global water system. *Journal of Hydrology*, *384*(3–4), 177–186. https://doi.org/10.1016/j.jhydrol.2009.06.026
47. IBM Corporation (2017). IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY: IBM Corporation
48. IHM, Institute for Health Metrics and Evaluation. (2019). *Global Burden of Disease (GBD): Cause of death in both sexes at all ages and related risk factors in Hungary*, University of Washington, Retrieved from: https://vizhub.healthdata.org/gbd-compare/ (last accessed: 02.06.2022.)
49. Jalava, M., Kummu, M., Porkka, M., Siebert, S., & Varis, O. (2014). Diet change - A solution to reduce water use? *Environmental Research Letters*, *9* 074016. https://doi.org/10.1088/1748-9326/9/7/074016
50. Jamovi (2020). The jamovi project, jamovi. (Version 1.2) (Computer Software). Available at: https://www. jamovi.org. (last accessed: 02.06.222.)
51. Jones, A. D., Hoey, L., Blesh, J., Miller, L., Green, A., & Shapiro, L. F. (2016). A Systematic Review of the Measurement of Sustainable Diets. *Advances in Nutrition: An International Review Journal*, *7*(4), 641–664. https://doi.org/10.3945/an.115.011015
52. Kemény G. (Szerk.), Lámfalusi I (Szerk.). & Molnár A. (Szerk.) (2018). *Az öntözhetőség természeti-gazdasági korlátainak hatása az öntözhető területekre*. Agrárgazdasági kutatóintézet, Budapest, 135 p
53. Kiss, A., Popp, J., Oláh, J., & Lakner, Z. (2019). The reform of school catering in Hungary: Anatomy of a health-education attempt. *Nutrients*, *11*(4), 1–19. https://doi.org/10.3390/nu11040716

54. Lares-Michel, M., Housni, F. E., Aguilera Cervantes, V. G., Carrillo, P., Michel Nava, R. M., & Llanes Cañedo, C. (2021). Eat Well to Fight Obesity… and Save Water: The Water Footprint of Different Diets and Caloric Intake and Its Relationship With Adiposity. *Frontiers in Nutrition*, *8*(July). https://doi.org/10.3389/fnut.2021.694775
55. Lluch, A., Maillot, M., Gazan, R., Vieux, F., Delaere, F., Vaudaine, S., & Darmon, N. (2017). Individual diet modeling shows how to balance the diet of french adults with or without excessive free sugar intakes. *Nutrients*, *9*(2). https://doi.org/10.3390/nu9020162
56. MacDiarmid, J. I. (2013). Is a healthy diet an environmentally sustainable diet? *Proceedings of the Nutrition Society*, *72*(1), 13–20. https://doi.org/10.1017/S0029665112002893
57. Maillot, M., Darmon, N., Darmon, M., Lafay, L., & Drewnowski, A. (2007). Nutrient-dense food groups have high energy costs: An econometric approach to nutrient profiling. *Journal of Nutrition*, *137*(7), 1815–1820. https://doi.org/10.1093/jn/137.7.1815
58. Maillot, M., Vieux, F., Amiot, M. J., & Darmon, N. (2010). Individual diet modeling translates nutrient recommendations into realistic and individual-specific food choices. *The American Journal of Clinical Nutrition*, *91*(2), 421–430. https://doi.org/10.3945/ajcn.2009.28426
59. Maillot, M., Vieux, F., Delaere, F., Lluch, A., & Darmon, N. (2017). Dietary changes needed to reach nutritional adequacy without increasing diet cost according to income: An analysis among French adults. *PLoS ONE 12*(3): e0174679. https://doi.org/ 10.1371/journal.pone.0174679
60. Masset, G., Soler, L. G., Vieux, F., & Darmon, N. (2014). Identifying sustainable foods: The relationship between environmental impact, nutritional quality, and prices of foods representative of the French diet. *Journal of the Academy of Nutrition and Dietetics*, *114*(6), 862–869. https://doi.org/10.1016/j.jand.2014.02.002
61. Masset, G., Vieux, F., & Darmon, N. (2015). Which functional unit to identify sustainable foods? *Public Health Nutrition*, *18*(13), 2488–2497. https://doi.org/10.1017/S1368980015000579
62. Masset, G., Vieux, F., Verger, E. O., Soler, L. G., Touazi, D., & Darmon, N. (2014). Reducing energy intake and energy density for a sustainable diet: A study based on self-selected diets in French adults. *American Journal of Clinical Nutrition*, *99*(6), 1460–1469. https://doi.org/10.3945/ajcn.113.077958
63. May, J. O., & Looney, S. W. (2020). Biometrics & Biostatistics Sample Size Charts for Spearman and Kendall Coefficients. *Journal of Biometrics & Biostatistics*, *11*(2), 5–11. https://doi.org/10.37421/jbmbs.2020.11.440
64. Meier, T., & Christen, O. (2012). Gender as a factor in an environmental assessment of the consumption of animal and plant-based foods in Germany. *International Journal of Life Cycle Assessment*, *17*(5), 550–564. https://doi.org/10.1007/s11367-012-0387-x
65. Mekonnen, M., & Hoekstra, A. Y. (2010a). Water Footprint Network (WFN). *The Green, Blue and Grey Water Footprint of Crops and Derived Crop Products*, UNESCO-IHE: Delft, The Netherlands; UNESCO-IHE Institute for Water Education: Delft, The Netherlands, 1–42. Retrieved from https://www.waterfootprint.org/en/resources/waterstat/product-water-footprint-statistics/ (last accessed: 02.06.022.)
66. Mekonnen, M., & Hoekstra, A. Y. (2010b). Water footprint Network (WFN). *The Green, Blue and Grey Water Footprint of Farm Animals and Animal Products,* UNESCO-IHE Institue for Water Education: Delft,The Netherlands, 1–50. Retrieved from https://www.waterfootprint.org/en/resources/waterstat/product-water-footprint-statistics/ (last accessed: 02.06.022.)

67. Meltzer, H. M., Brantsæter, A. L., Trolle, E., Eneroth, H., Fogelholm, M., Ydersbond, T. A., & Birgisdottir, B. E. (2019). Environmental Sustainability Perspectives of the Nordic Diet. *Nutrients*, *11*(9), 1–18. https://doi.org/10.3390/nu11092248
68. Microsoft Corporation. (2018). Microsoft Excel. Retrieved from https://office.microsoft.com/excel (last accessed: 02.06.2022.)
69. Milner, J., Joy, E. J. M., Green, R., Harris, F., Aleksandrowicz, L., Agrawal, S., … Haines, A. (2017). Articles Projected health effects of realistic dietary changes to address freshwater constraints in India: a modelling study. *Lancet Planet Health*, *1*(1), e26–e32. https://doi.org/10.1016/S2542-5196(17)30001-3
70. Ministry of Human Capacities (2014): Public Catering Act - EMMI Decree 37/2014. (IV.30), [37/2014. (IV. 30.) EMMI rendelet a közétkeztetésre vonatkozó táplálkozás-egészségügyi előírásokról]
71. Mozaffarian, D., & Ludwig, D. S. (2010). Dietary guidelines in the 21st century - A time for food. *JAMA - Journal of the American Medical Association*, *304*(6), 681–682. https://doi.org/10.1001/jama.2010.1116
72. Mozaffarian, D., Appel, L. J., & Van Horn, L. (2011). Components of a cardioprotective diet: New insights. *Circulation*, *123*(24), 2870–2891. https://doi.org/10.1161/CIRCULATIONAHA.110.968735
73. Nagy, B., Nagy-Lőrincz, Z., Bakacs, M., Illés, É., Sarkadi Nagy, E., Erdei, G., & Martos, É. (2017). Országos Táplálkozás és Tápláltsági Állapot Vizsgálat – OTÁP2014. IV. A magyar lakosság mikroelem-bevitele. [Hungarian Dietary and Nutritional Status Survey – HDNSS 2014. IV. The micronutrient intake of the Hungarian Population] *Orvosi Hetilap*, *158*(21), 803–810. https://doi.org/10.1556/650.2017.30773
74. Nagypál, V., Mikó, E., & Hodúr, C. (2020). Sustainable water use considering three Hungarian dairy farms. *Sustainability*, *12*(8), 3145. https://doi.org/10.3390/SU12083145
75. Nagypál, V., Mikó, E., Czupy, I., & Hodúr, C. (2019). Water footprint. *Analecta Technica Szegedinensia*, *13*(2), 12–20. https://doi.org/10.14232/analecta.2019.2.12-20
76. National Tax and Custom Administration. Act CIII of 2011 on Public Health Product Tax. 2011. [Nemzeti Adó- és Vámhivatal, A népegészségügyi termékadóról szóló 2011. évi CIII. Törvénye] Available online: https: //extranet.who.int/nutrition/gina/en/node/26174
77. Nohr, D., & Biesalski, H. K. (2007). “Mealthy” food: Meat as a healthy and valuable source of micronutrients. *Animal*, *1*(2), 309–316. https://doi.org/10.1017/S1751731107657796
78. Nutricomp étrend [diet] 4.0. (2014). *Nutricomp*. Budapest: Nutricomp Bt. Retrieved from https://www.nutricomp.hu/ (last accessed: 02.06.2022.)
79. Okostányér® [Smartplate]. (2016). Magyar Dietetikusok Országos Szövetség [Hungarian Association of Dietitians] Retrieved from: https://www.okostanyer.hu/wp-content/uploads/2021/11/2021_OKOSTANYER_ANGOL_felnott_A4.pdf (last accessed: 02.06.2022.)
80. Perignon, M., Masset, G., Ferrari, G., Barré, T., Vieux, F., Maillot, M., … Darmon, N. (2016a). How low can dietary greenhouse gas emissions be reduced without impairing nutritional adequacy, affordability and acceptability of the diet? A modelling study to guide sustainable food choices. *Public Health Nutrition*, *19*(14), 2662–2674. https://doi.org/10.1017/S1368980016000653
81. Perignon, M., Masset, G., Ferrari, G., Barré, T., Vieux, F., Maillot, M., … Darmon, N. (2016a). How low can dietary greenhouse gas emissions be reduced without impairing nutritional adequacy, affordability and acceptability of the diet? A modelling study to guide

sustainable food choices. – Online supplemental materials. *Public Health Nutrition*, *19*(14), 2662–2674. https://doi.org/10.1017/S1368980016000653

82. Perignon, M., Vieux, F., Soler, L. G., Masset, G., & Darmon, N. (2017). Improving diet sustainability through evolution of food choices: Review of epidemiological studies on the environmental impact of diets. *Nutrition Reviews*, *75*(1), 2–17. https://doi.org/10.1093/nutrit/nuw043
83. R Core Team (2019). R: a language and environment for statistical computing. (Version 3.6) (Computer software). Retrieved from: https://cran.r-project.org/ (last accessed: 02.06.2022.)
84. Rodler, I. (2005). *Új tápanyagtáblázat* [*New Food Composition Table]*. Budapest: Medicina könyvkiadó.
85. Röös, E., Karlsson, H., Witthöft, C., & Sundberg, C. (2015). Evaluating the sustainability of diets-combining environmental and nutritional aspects. *Environmental Science and Policy*, *47*, 157–166. https://doi.org/10.1016/j.envsci.2014.12.001
86. Rutten, M., Achterbosch, T. J., de Boer, I. J. M., Cuaresma, J. C., Geleijnse, J. M., Havlík, P.,…Zurek, M. (2018). Metrics, models and foresight for European sustainable food and nutrition security: The vision of the SUSFANS project. *Agricultural Systems*, *163*, 45–57. https://doi.org/10.1016/j.agsy.2016.10.014
87. Saarinen, M., Fogelholm, M., Tahvonen, R., & Kurppa, S. (2017). Taking nutrition into account within the life cycle assessment of food products. *Journal of Cleaner Production*, *149*, 828–844. https://doi.org/10.1016/j.jclepro.2017.02.062
88. Sáez-Almendros, S., Obrador, B., Bach-Faig, A., & Serra-Majem, L. (2013). Environmental footprints of Mediterranean versus Western dietary patterns: Beyond the health benefits of the Mediterranean diet. *Environmental Health: A Global Access Science Source*, *12*(1), 1–8. https://doi.org/10.1186/1476-069X-12-118
89. Sarkadi Nagy, E., Bakacs M., Illés É., Varga A & Martos É. (2016). HDNSS. *Az Országos Táplálkozás és Tápláltsági Állapot Vizsgálat OTÁP 2014 főbb eredményei – előadás [Main results of the Hungarian Dietary and Nutritional Status Survey 2014 – presentation]* Available at: https://ogyei.gov.hu/dynamic/5_sarkadi_otap2014_makrotap.pdf (last accessed:02.06.2022.)
90. Sarkadi Nagy, E., Bakacs, M., Illés, É., Nagy, B., Varga, A., Kis, O., … & Martos, É. (2017). Országos Táplálkozás és Tápláltsági Állapot Vizsgálat – OTÁP2014. II. A magyar lakosság energia- és makrotápanyag-bevitele. [Hungarian Dietary and Nutritional Status Survey – HDNSS 2014. IV. The energy and macronutrient intake of the Hungarian Population] *Orvosi Hetilap*, *158*(15), 587–597. https://doi.org/10.1556/650.2017.30718
91. Scarborough, P., Allender, S., Clarke, D., Wickramasinghe, K., & Rayner, M. (2012). Modelling the health impact of environmentally sustainable dietary scenarios in the UK. *European Journal of Clinical Nutrition*, *66*(6), 710–715. https://doi.org/10.1038/ejcn.2012.34
92. Scheelbeek, P., Green, R., Papier, K., Knuppel, A., Alae-Carew, C., Balkwill, A., … Dangour, A. D. (2020). Health impacts and environmental footprints of diets that meet the Eatwell Guide recommendations: analyses of multiple UK studies. *BMJ Open*, *10*(8), e037554. https://doi.org/10.1136/bmjopen-2020-037554
93. Schreiberné Molnár, E., Nagy-Lőrincz, Z., Nagy, B., Bakacs, M., Kis, O., Sarkadi Nagy, E., & Martos, É. (2017). Országos Táplálkozás- és Tápláltsági Állapot Vizsgálat – OTÁP2014. V. A magyar lakosság vitaminbevitele [Hungarian Dietary and Nutritional Status Survey – HDNSS 2014. IV. The vitamin intake of the Hungarian Population]. *Orvosi Hetilap*, *158*(33), 1302–1313. https://doi.org/10.1556/650.2017.30832

94. Schüpbach, R., Wegmüller, R., Berguerand, C., Bui, M., & Herter-Aeberli, I. (2017). Micronutrient status and intake in omnivores, vegetarians and vegans in Switzerland. *European Journal of Nutrition*, *56*(1), 283–293. https://doi.org/10.1007/s00394-015-1079-7
95. Shim, J., Oh, K., & Kim, H. C. (2014). Dietary assessment methods in epidemiologic studies. *Epidemiology and Health 36*, 1–8. http://dx.doi.org/10.4178/epih/e2014009.
96. Song, G., Li, M., Fullana-i-Palmer, P., Williamson, D., & Wang, Y. (2017). Dietary changes to mitigate climate change and benefit public health in China. *Science of the Total Environment*, *577*, 289–298. https://doi.org/10.1016/j.scitotenv.2016.10.184
97. Springmann, M., Wiebe, K., Croz, D. M., Sulser, T. B., Rayner, M., & Scarborough, P. (2018). Articles Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. *The Lancet Planetary Health*, *2*(10), e451–e461. https://doi.org/10.1016/S2542-5196(18)30206-7
98. Steenson, S., & Buttriss, J. L. (2021). Healthier and more sustainable diets: What changes are needed in high-income countries? *Nutrition Bulletin*, *46*(3), 279–309. https://doi.org/10.1111/nbu.12518
99. Tepper, S., Kissinger, M., Avital, K., & Shahar, D. R. (2022). The Environmental Footprint Associated With the Mediterranean Diet, EAT-Lancet Diet , and the Sustainable Healthy Diet Index : A Population-Based Study. *Frontiers in Nutrition* 9(May), 1–11. https://doi.org/10.3389/fnut.2022.870883
100. Tom, M. S., Fischbeck, P. S., & Hendrickson, C. T. (2016). Energy use, blue water footprint, and greenhouse gas emissions for current food consumption patterns and dietary recommendations in the US. *Environment Systems and Decisions*. https://doi.org/10.1007/s10669-015-9577-y
101. Tompa, O., Kanalas, O., Kiss, A., Soós, S., & Lakner, Z. (2021). Integrative analysis of dietary water footprint and dietary quality – Towards the practical application of sustainable nutrition. *Acta Alimentaria*. https://doi.org/10.1556/066.2021.00070
102. Tompa, O., Kiss, A., & Lakner, Z. (2020). Towards the sustainable food consumption in central Europe: Stochastic relationship between water footprint and nutrition. *Acta Alimentaria, 49*(1), 86–92. https://doi.org/10.1556/066.2020.49.1.11
103. Tompa, O., Kiss, A., Maillot, M., Sarkadi Nagy, E., Temesi, Á. & Lakner, Z., (2022). Sustainable Diet Optimization Targeting Dietary Water Footprint Reduction — A Country-Specific Study. *Sustainability*. 14, 2309. https://doi.org/10.3390/su14042309
104. Tompa, O., Lakner, Z., Oláh, J., Popp, J., & Kiss, A. (2020). Is the sustainable choice a healthy choice? – water footprint consequence of changing dietary patterns. *Nutrients*, *12*(9), 1–19. https://doi.org/10.3390/nu12092578
105. UN, United Nations. (2015). *Sustainable Development Goals (SDGs)*. Available at: https://sdgs.un.org/goals (last accessed: 02.06.2022.)
106. USDA, U.S. Department of Agriculture (2015). A Series of Systematic Reviews on the Relationship Between Dietary Patterns and Health Outcomes. Arlington, VA. [cited 3 October 2019]. Retrieved from: https://nesr.usda.gov/dietary-patterns-foods-and-nutri-ents-and-health-outcomes-subcommittee (last accessed: 31.08.2022.)
107. USDA, U.S. Department of Agriculture. (2018). USDA Food and Nutrient Database for Dietary Studies 2017-2018, U.S. Department of Agriculture, Agricultural Research Service, Food Surveys Research Group Home Page, Retrieved from: https://www.ars.usda.gov/northeast-area/beltsville-md-bhnrc/beltsville-human-nutrition-

research-center/food-surveys-research-group/docs/fndds-download-databases/ (last accessed: 02.06.2022.)

108. van Dooren, C., (2018). A Review of the Use of Linear Programming to Optimize Diets, Nutritiously, Economically and Environmentally. *Frontiers in Nutrition*, *5*(June). https://doi.org/10.3389/fnut.2018.00048
109. van Dooren, C., Douma, A., Aiking, H., & Vellinga, P. (2017). Proposing a Novel Index Reflecting Both Climate Impact and Nutritional Impact of Food Products. *Ecological Economics*, *131*, 389–398. https://doi.org/10.1016/j.ecolecon.2016.08.029
110. van Dooren, C., Man, L., Seves, M., & Biesbroek, S. (2021). A Food System Approach for Sustainable Food-Based Dietary Guidelines: An Exploratory Scenario Study on Dutch Animal Food Products. *Frontiers in Nutrition*, *8*(September), 1–14. https://doi.org/10.3389/fnut.2021.712970
111. van Dooren, C., Marinussen, M., Blonk, H., Aiking, H., & Vellinga, P. (2014). Exploring dietary guidelines based on ecological and nutritional values: A comparison of six dietary patterns. *Food Policy*, *44*, 36–46. https://doi.org/10.1016/j.foodpol.2013.11.002
112. Vanham, D. (2013). The water footprint of Austria for different diets. *Water Science and Technology*, *67*(4), 824–830. https://doi.org/10.2166/wst.2012.623
113. Vanham, D., Hoekstra, A. Y., & Bidoglio, G. (2013). Potential water saving through changes in European diets. *Environment International*, *61*, 45–56. https://doi.org/10.1016/j.envint.2013.09.011
114. Vanham, D., Leip, A., Galli, A., Kastner, T., Bruckner, M., Uwizeye, A., … Hoekstra, A. Y. (2019). *Science of the Total Environment Environmental footprint family to address local to planetary sustainability and deliver on the SDGs*. *693*(June). https://doi.org/10.1016/j.scitotenv.2019.133642
115. Vanham, D., Mekonnen, M. M., & Hoekstra, A. Y. (2013). The water footprint of the EU for different diets. *Ecological Indicators*, *32*, 1–8. https://doi.org/10.1016/j.ecolind.2013.02.020
116. Vanham, D., Mekonnen, M., & Hoekstra, A. Y. (2020). Treenuts and groundnuts in the EAT-Lancet reference diet: Concerns regarding sustainable water use. *Global Food Security*. *24*(September 2019). https://doi.org/10.1016/j.gfs.2020.100357
117. Vanham, Davy. (2020). Water resources for sustainable healthy diets: State of the art and outlook. *Water (Switzerland)*, *12*(11), 1–15. https://doi.org/10.3390/w12113224
118. Vetőné Mózner, Z. (2014). Az élelmiszer-fogyasztás szerkezete és környezeti hatása Magyarországon. *Marketing & Menedzsment*, *3*, 57-69.
119. Vettori, V., Bronzi, B., Lorini, C., Cavallo, G., & Bonaccorsi, G. (2021). Widespread dietary patterns (Healthy and balanced diet, western diet, and vegan and vegetarian diets) compared for water consumption: Which is the winner? *Sustainability (Switzerland)*, *13*(21). https://doi.org/10.3390/su132111946
120. Vieux, F., Darmon, N., Touazi, D., & Soler, L. G. (2012). Greenhouse gas emissions of self-selected individual diets in France: Changing the diet structure or consuming less? *Ecological Economics*, *75*, 91–101. https://doi.org/10.1016/j.ecolecon.2012.01.003
121. Vieux, F., Privet, L., Soler, L. G., Irz, X., Ferrari, M., Sette, S., … Darmon, N. (2020). More sustainable European diets based on self-selection do not require exclusion of entire categories of food. *Journal of Cleaner Production*, *248*, 119298. https://doi.org/10.1016/j.jclepro.2019.119298
122. Vieux, F., Perignon, M., Gazan, R., & Darmon, N. (2018). Dietary changes needed to improve diet sustainability: Are they similar across Europe? *European Journal of Clinical Nutrition*, *72*(7), 951–960. https://doi.org/10.1038/s41430-017-0080-z

123. Vieux, F., Soler, L.-G., Touazi, D., & Darmon, N. (2013). High nutritional quality is not associated with low greenhouse gas emissions in self-selected diets of French adults. *The American Journal of Clinical Nutrition*, *97*(3), 569–583. https://doi.org/10.3945/ajcn.112.035105
124. Water Footprint Network (WFN). What Is Waterfootprint? 2020. Available at: https://waterfootprint.org/en/water-footprint/what-is-water-footprint/ (last accessed: 02.06.2022.)
125. WHO, FAO and UNU. (2007)., World Health Organization, Food and Agriculture Organization of the United Nations and United Nations University. Expert Consultation on Protein and amino acid requirements in human nutrition Expert Consultation on Protein and amino acid requirements in human nutrition. *In World Health Organization technical report series* https://doi.org/ISBN 92 4 120935 6, Available at: https://www.fao.org/3/i1953e/I1953E.pdf (last accessed:02.06.2022.)
126. Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L., François, R., … Yutani, H. (2019). Welcome to the Tidyverse. *Journal of Open Source Software*, *4*(43), 1686. https://doi.org/10.21105/joss.01686
127. Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., … Murray, C. (2019). Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *Lancet*, *6736*(18), 3–49. https://doi.org/10.1016/S0140-6736(18)31788-4

10.2. List of publications on the field of science

International IF journal articles

Tompa, O., Kiss, A., Maillot, M., Nagy, E. S.,Temesi, Á. & Lakner Z.(2022). Sustainable Diet Optimization Targeting Dietary Water Footprint Reduction — A Country-Specific Study. Sustainability, 14(4), 2309; https://doi.org/10.3390/su14042309, **IF: 4.17, Q1**

Tompa, O., Kanalas O., Kiss, A., Soós S., & Lakner, Z. (2021). Integrative analysis of dietary water footprint and dietary quality – Towards the practical application of sustainable nutrition. Acta Alimentaria. https://doi.org/10.1556/066.2021.00070, **IF: 0.65, Q3**

Tompa, O., Lakner, Z., Oláh J., Popp J., & Kiss, A., (2020). Is the Sustainable Choice a Healthy Choice?—Water Footprint Consequence of Changing Dietary Patterns. Nutrients, 12(9), 1–19. https://doi.org/10.3390/nu12092578, **IF: 5.43, Q1**

Tompa, O., Kiss, A., & Lakner, Z. (2020). Towards the sustainable food consumption in central Europe: Stochastic relationship between water footprint and nutrition. Acta Alimentaria, 49(1), 86–92. https://doi.org/10.1556/066.2020.49.1.11, **IF: 0.65, Q3**

International conference presentations

Tompa O., Kanalas O., Plasek, B.; Anna, Kiss, Analysis of the association between the healthiness and ecological footprint of nutrition and body composition - a methodological approach In: Fodor, Marietta; Bodor-Pesti, Péter; Deák, Tamás (eds.) SZIEntific Meeting for Young Researchers 2020 : ITT Ifjú Tehetségek Találkozója 2020, Bp, Hungary : SZIE Budai Campus (2021) 437 p. pp. 416-419. , 4 p., lecture

Tompa, O., Kiss A., Lakner, Z., Lecture: Association of the Hungarian Food Consumption Structure and Water Footprint, Tavaszi Szél Konferencia 2019, Nemzetközi Multidiszciplináris Konferencia, Doktoranduszok Országos Szövetsége, 2019.05.03-05., ISBN 978-615-5586-42-2, pp 89-90.,

Tompa, O., Kiss A., Lakner, Z., Lecutre: Analysis of different dietary scenarios based on the Hungarian nutrition from the aspect of health and sustainability, 19th International Nutrition & Diagnostics Conference (INDC) 2019.10.15-18., Prague, pp 39.

International conference full papers

Tompa O.; Kanalas O., Plasek, B.; Anna, Kiss, Analysis of the association between the healthiness and ecological footprint of nutrition and body composition - a methodological approachIn: Fodor, Marietta; Bodor-Pesti, Péter; Deák, Tamás (eds.) SZIEntific Meeting for Young Researchers 2020 : ITT Ifjú Tehetségek Találkozója 2020, Bp, Hungary : SZIE Budai Campus (2021) 437 p. pp. 416-419. , 4 p., conference paper

Hungarian conference presentations

Tompa, O., Lakner, Z., Fenntartható táplálkozás a fejlődő országokban: az élelmiszer-fogyasztás optimalizálása, Magyar Tudományos Akadémia, Kertészeti és Élelmiszertudományi Bizottság, Élelmiszertudományi Albizottság, 2018.12.06., ISBN: 978-963-508-900-0, pp 21.

Tompa, O., Kiss A., Lakner, Z., Hivatalos, élelmiszeralapú, fenntartható táplálkozási ajánlások összehasonlító elemzése, I. Országos Táplálkozástudományi Szakemberek Konferenciája, Debrecen, 2019.03.09., ISBN 978-963-490-075-7, 99 17., pp 18.

Tompa, O., Kiss A., Lakner, Z., Különböző étrendi szcenáriók elemzése fenntarthatósági és egészségességi szempontok alapján, Magyar Táplálkozástudományi Társaság XLIV. Vándorgyűlése, Székesfehérvár, 2019.03-05., ISBN 978-615-5606-09-0, pp 50.

Kiss, A., **Tompa, O.**, Fenntarthatóság a sporttáplálkozásban? A rekreáció sokszínűsége" c. Leisure konferencia, 2019.10.15.. Miskolc

International poster presentations

Tompa, O., Kiss A., Lakner, Z., Poster presentation: Analysis and optimization of the structure of food supply in Ethiopia, Africa and Europe Moving Forward - Evidence-based Solutions for African Development, 2019.01.24-26., Lüneburg, Leuphana University

Kiss, A., **Tompa, O.**, Lakner, Z., Poster presentation: Future of food supply in Africa-a system dynamic, network-based approach, Africa and Europe Moving Forward - Evidence-based Solutions for African Development, 2019.01.24-26., Lüneburg, Leuphana University

Tompa, O., Kiss A., Lakner, Z., Poster presentation: Estimation of food and nutrient intake based on the two opposite extemities – an experimental approach in case of Hungary, 19th International Nutrition & Diagnostics Conference (INDC) 2019.10.15-18., Prague, pp 119.

10.3. Supplementary Materials (numbered)

SM Table 1. Classification of food groups and sub-groups (S_4) (Tompa et al, 2022).

Food groups	Food sub-groups
Alcoholic drinks	Wines
Alcoholic drinks	Beers
Drinks	Fruit and vegetable juices
Drinks	Carbonated soft drinks
Drinks	Smoothies
Eggs and products	Eggs
Fats and oils	Animal fats
Fats and oils	Vegetable oils
Fruits and products	Nuts and seeds
Fruits and products	Fruit products
Fruits and products	Fresh and frozen fruits
Fruits and products	Jams
Grains	Cereals, groats and grains
Grains	Whole grain bread
Grains	Wheat Bread
Grains	Dry pasta
Grains	Rolls
Meats and products	Meat products
Meats and products	Poultry meat
Meats and products	Pork meat
Meats and products	Beef meat
Meats and products	Fishes incl. canned fishes
Meats and products	Offals and products
Milk and dairies	Fermented dairy products
Milk and dairies	Milk and milk-based drinks
Milk and dairies	Cottage cheese
Milk and dairies	Cheese
Milk and dairies	Other dairies and creams
Sauces and seasonings	Sauces and seasonings
Sweets	Bakery products, pastries and sweets
Sweets	Sugar and honey
Vegetables and products	Legumes and products
Vegetables and products	Canned vegetables and vegetable products
Vegetables and products	Fresh and frozen vegetables incl. mushrooms
Vegetables and products	Potatoes

SM Table 2. Cultural acceptability constraints on food sub-groups: 10th (as a minimum constraint) and 90th (as maximum constraint) percentiles, observed (as a maximum constraint in specific cases) and optimized amount (g/day/capita) of food sub-groups for women (S^4) (Tompa et al. 2022).

10th and 90th percentiles of population food sub-group and group intake were estimated based on the representative population sample (women: n = 485) from HDNSS 2014 study) (Sarkadi et al., 2017).

* Maximum constraint equals observed intake instead of 90th percentile for food groups to be limited based on recommendations (EC, 2016a; IHM, 2019; Okostányér®, 2016)

Red: equals maximum constraint, Yellow: equals minimum constraint, Orange: equals both minimum and maximum constraint.

		Women				
Food sub-groups	10th percentile (min. constraint)	90th percentile or observed mean*(max constraint)	Observed mean intake	WFP_OBS	WFP-10%	WFP-18%
Cereals, groats and grains	17.7	104.0	55.9	31.9	37.9	50.3
Nuts and seeds	0.0	20.4	7.4	20.4	20.4	20.4
Legumes and products	0.0	16.7	4.8	4.8	4.8	10.6
Whole grain bread	0.0	66.7	18.3	66.7	66.7	66.7
Canned vegetables and vegetable products	0.0	88.1	30.5	71.9	86.1	72.6
Bakery products, pastries and sweets*	0.0	18.9*	18.9	4.5	4.5	4.5
Wheat Bread	0.0	120.0	46.0	115.8	118.6	120.0
Fruit products	0.0	33.3	8.6	8.6	8.6	8.6
Fresh and frozen fruits	1.6	373.3	177.5	292.2	293.5	283.3
Dry pasta	0.0	51.3	19.8	16.6	0.0	0.0
Rolls	0.0	100.0	41.4	41.4	33.9	16.5
Fresh and frozen vegetables incl. mushrooms	55.9	307.7	174.7	307.7	307.7	307.7
Potatoes	0.0	166.7	76.2	63.5	49.3	57.0
Jams	0.0	15.5	4.6	0.0	0.0	0.0
Fruit and vegetable juices	0.0	136.3	44.5	44.5	44.5	44.5
Sauces and seasonings	4.5	19.4	11.1	11.1	11.1	11.1
Meat products*	0.0	42.4*	42.4	0.0	0.0	0.0
Fermented dairy products	0.0	125.0	40.8	93.4	89.8	125.0
Milk and milk-based drinks	5.0	365.9	159.6	159.6	159.6	45.1
Cottage cheese	0.0	30.0	9.6	9.6	0.0	0.0
Cheese	0.0	51.3	19.2	0.0	0.0	0.0
Other dairies and creams	0.0	45.0	20.6	0.0	0.0	0.0
Eggs	3.3	51.0	22.7	51.0	51.0	51.0
Poultry meat	0.0	113.3	54.0	71.0	113.3	113.3
Pork meat	0.0	83.3	33.2	33.2	22.0	32.2
Beef meat	0.0	16.4	3.2	9.7	3.2	0.6
Fishes incl. canned fishes	0.0	27.2	5.3	5.3	8.8	22.7

Offals and products*	0.0	7.4*	7.4	7.4	7.4	7.4
Animal fats	0.0	26.9	9.8	0.0	0.0	0.0
Vegetable oils	14.8	52.9	30.9	27.2	27.3	27.2
Sugar and honey*	3.3	23.7*	23.7	3.3	3.3	3.3
Wines*	0.0	9.5*	9.5	9.5	9.5	0.0
Beers*	0.0	11.1*	11.1	11.1	11.1	11.1
Carbonated soft drinks*	0.0	42.2*	42.2	0.0	0.0	0.0
Smoothies	0.0	0.0	4.6	0.0	0.0	0.0

SM Table 3. Cultural acceptability constraints on food sub-groups: 10th (as a minimum constraint) and 90th (as maximum constraint) percentiles, observed (as a maximum constraint in specific cases) and optimized amount (g/day/capita) of food sub-groups for men (S^4) (Tompa et al. 2022).

10th and 90th percentiles of population food sub-group and group intake were estimated based on the representative population sample (men: n = 372) from HDNSS 2014 study) (Sarkadi Nagy et al., 2017).

* Maximum constraint equals observed intake instead of 90th percentile for food groups to be limited based on recommendations (EC, 2016a; IHM, 2019; Okostányér®, 2016)

Red: equals maximum constraint, Yellow: equals minimum constraint, Orange: equals both minimum and maximum constraint.

	Men					
Food sub-groups	10th percentile (min. constraint)	90th percentile or observed mean*(max. constraint)	Observed mean intake	WFP_OBS	WFP-15%	WFP-28%
Cereals, groats and grains	15.0	115.1	61.3	113.1	100.1	115.1
Nuts and seeds	0.0	20.0	6.4	6.4	20.0	20.0
Legumes and products	0.0	16.7	4.2	4.2	4.2	16.7
Whole grain bread	0.0	66.0	17.0	66.0	66.0	66.0
Canned vegetables and vegetable products	0.0	124.8	44.1	101.6	54.0	71.3
Bakery products, pastries and sweets*	0.0	18.1*	18.1	0.0	0.0	0.0
Wheat Bread	0.0	224.5	103.2	117.8	217.5	220.8
Fruit products	0.0	13.1	6.0	6.0	6.0	6.0
Fresh and frozen fruits	0.0	366.3	160.7	160.7	160.7	45.2
Dry pasta	0.0	57.3	23.1	23.1	23.1	4.8
Rolls	0.0	139.9	51.9	39.8	0.0	0.0
Fresh and frozen vegetables incl. mushrooms	50.1	322.7	180.7	322.7	322.7	322.7
Potatoes	0.0	241.3	100.2	100.2	13.2	100.2
Jams	0.0	19.9	4.8	4.8	4.8	4.8
Fruit and vegetable juices	0.0	153.0	46.9	46.9	46.9	0.0
Sauces and seasonings	5.7	21.9	12.9	12.9	12.9	5.7
Meat products*	15.0	81.1*	81.1	15.0	15.0	15.0
Fermented dairy products	0.0	124.5	33.1	33.8	83.0	124.5
Milk and milk-based drinks	0.0	410.8	173.7	173.7	123.9	50.2
Cottage cheese	0.0	29.3	10.2	10.2	10.2	0.0
Cheese	0.0	59.9	21.9	0.0	0.0	0.0
Other dairies and creams	0.0	50.0	23.8	0.0	0.0	0.0
Eggs	3.7	74.9	34.8	55.3	74.9	74.9
Poultry meat	0.0	126.3	56.0	126.3	126.3	126.3
Pork meat	0.0	121.5	50.6	50.6	54.1	39.0
Beef meat	0.0	25.0	5.1	21.1	5.1	3.6
Fishes incl. canned fishes	0.0	33.3	7.5	7.5	7.5	7.5

Offals and products*	0.0	10.7*	10.7	10.7	10.7	10.7
Animal fats	0.0	46.4	16.9	0.0	0.0	0.0
Vegetable oils	15.7	57.2	36.3	43.6	38.6	40.3
Sugar and honey*	2.1	25.4*	25.4	4.7	4.7	5.4
Wines*	0.0	30.1*	30.1	30.1	30.1	0.0
Beers*	0.0	99.9*	99.9	99.9	0.0	0.0
Carbonated soft drinks*	0.0	77.4*	77.4	77.4	77.4	77.4
Smoothies	0.0	0.0	14.9	0.0	0.0	0.0

SM Table 4. Cultural acceptability constraints on main food groups 10th (as a minimum constraint) and 90th (as minimum constraint) percentiles, observed (as a maximum constraint in specific cases) and optimized amount (g/day/capita) of food sub-groups for women (S_4) (Tompa et al. 2022).

10th and 90th percentiles of population food sub-group and group intake were estimated based on the representative population sample (women: n = 485) from HDNSS 2014 study (Sarkadi Nagy, 2017)

Maximum constraint equals observed intake instead of 90th percentile for “Alcoholic drinks” due to their “behavioral risk” status contributing to the development of non-communicable diseases (IHM, 2019).

Red: equals maximum constraint, Yellow: equals minimum constraint, Orange: equals both minimum and maximum constraint.

	Women					
Food groups	10th percentile (min. constraint)	90th percentile or observed mean*(max constraint)	Observed mean intake	WFP_OBS	WFP-10%	WFP-18%
Alcoholic drinks*	0.0	20.7*	20.7	20.7	20.7	11.1
Drinks	0.0	300.0	91.3	44.5	44.5	44.5
Eggs and products	3.3	51.0	22.7	51.0	51.0	51.0
Fats and oils	21.4	63.2	40.7	27.2	27.3	27.2
Fruits products	23.3	394.3	198.0	321.2	322.5	312.3
Grains	92.7	273.9	181.4	272.3	257.1	253.5
Meats and products	63.3	229.3	145.6	126.7	154.8	176.1
Milk and dairies	63.3	479.1	249.8	262.6	249.4	170.1
Sauces and seasonings	4.5	19.4	11.1	11.1	11.1	11.1
Sweets	7.8	87.7	42.6	7.8	7.8	7.8
Vegetables	135.9	447.9	286.2	447.9	447.9	447.9

SM Table 5. Cultural acceptability constraints on main food groups 10th (as a minimum constraint) and 90th (as minimum constraint) percentiles, observed (as a maximum constraint in specific cases) and optimized amount (g/day/capita) of food sub-groups for men (S_4) (Tompa et al. 2022).

10th and 90th percentiles of population food sub-group and group intake were estimated based on the representative population sample (men: n = 372) from HDNSS 2014 study (Sarkadi Nagy, 2017)

Maximum constraint equals observed intake instead of 90th percentile for “Alcoholic drinks” due to their “behavioral risk” status contributing to the development of non-communicable diseases (IHM, 2019).

Red: equals maximum constraint, Yellow: equals minimum constraint, Orange: equals both minimum and maximum constraint.

Men						
Food groups	10th percentile (min. constraint)	90th percentile or observed mean*(max constraint)	Observed mean intake	WFP_OBS	WFP-15%	WFP-28%
Alcoholic drinks*	0.0	130.0*	130.0	130.0	30.1	0.0
Drinks	0.0	493.3	139.2	124.3	124.3	77.4
Eggs and products	3.7	74.9	34.8	55.3	74.9	74.9
Fats and oils	25.0	86.9	53.2	43.6	38.6	40.3
Fruits products	0.0	391.7	178.0	178.0	191.6	76.0
Grains	130.3	406.7	256.5	359.8	406.7	406.7
Meats and products	96.7	326.7	210.9	231.2	218.7	202.0
Milk and dairies	44.7	538.0	262.7	217.7	217.1	174.7
Sauces and seasonings	5.7	21.9	12.9	12.9	12.9	5.7
Sweets	4.7	96.7	43.5	4.7	4.7	5.4
Vegetables	142.0	532.4	329.2	528.7	394.2	510.9

SM List 1.: The most commonly consumed foods and/or categories in Hungary (n = 44), (CSO, 2018), (S_1),

wheat and products; rice (milled equivalent); rye and products; pig meat, poultry meat; eggs; bovine meat; offals, edible; fats; animals, raw; sunflower seed oil; palm oil; rape and mustard oil; soyabean oil; cream; potatoes and products; tomatoes and products; onions; peas; sugar (raw equivalent); cocoa beans and products; apples and products; oranges, mandarins; grapes and products (excl wine); bananas; citrus, other; beer; wine; beverages, alcoholic; cheese; yoghurt; leafy; cabbage; cucumber; paprika; pulses; carrot; apricot; peach; cherry/sour cherry; berries; pulm; pear; watermelon; nuts.

SM Table 6. List of food groups and items and their weight in the calculation (CSO, 2018; FAO 2020), (S3), (Tompa, Lakner et al., 2020)

Food groups	Food items	Supply (g/day/capita)
Based on the classification of HDNSS, 2014	The supply of the food items is mostly based on FAO FBS and specified with the database of Central Statistical Office of Hungary. In the calculation of weighted average water footprint and nutrient values of the scenarios, supply quantities were used as weight in 1:1 proportion. In the case of "Fruits, others and Vegetables, others" the simple average was calculated based on the most commonly consumed food items.	
Grains	Wheat and products	301
	Rice (Milled Equivalent)	6
	Rye and products	4
Meat and meat products (including eggs)	Pig meat	96
	Poultry Meat	65
	Eggs	34
	Bovine Meat	14
	Freshwater Fish	7
	Offals, Edible	4
	Fish	14
Fats and oils	Fats, Animals, Raw	35
	Sunflower seed Oil	30
	Palm Oil	13
	Rape and Mustard Oil	6
	Soybean Oil	4
Milk and dairy products	Milk - Excluding Butter (-yoghurt and cheese)	388
	Cheese	16
	Yoghurt	32
	Cream	18
Vegetables	Vegetables, Other	158
	Potatoes and products	127
	Tomatoes and products	41
	Onions	18
	Peas	6
	Vegetables, other:	
	Leafy vegetables	
	Cabbage	
	Cucumber	
	Green pepper	

	Beans	
	Carrot	
Sweets	Sugar (Raw Equivalent)	52
	Sweeteners, Other	43
	Cocoa Beans and products	7
Fruits	Fruits, Other	64
	Apples and products	29
	Oranges, Mandarins	29
	Grapes and products (excl. wine)	16
	Bananas	9
	Citrus, Other	4
	Pimento	4
	Nuts and products	4
	Fruit, others:	
	Apricot	
	Peach	
	Cherry/sour cherry	
	Berries	
	Pulm	
	Pear	
	Watermelon	
	Nuts	
	Raisin	
Alcoholic drinks	Beer	176
	Wine	66
	Spirits	17

SM Table 7. Dietary reference values included in the dietary quality scores (Nagy et al., 2017; Rodler, 2005; Sarkadi Nagy et al., 2016, 2017; Schreiberné Molnár, 2017), (S3), Tompa, Lakner et al. 2020)

SM Table 7.a.: Energy and macronutrients

Macronutrients with recommended intake range (values are calculated based on the reference humans (Table 7.g.))

		Total protein (g)		Total carbohydrate (g)		Total fat (g)	
		HUN	EFSA	HUN	EFSA	HUN	EFSA
Male	min	60	62	330	278	76	55
	max	90	125	360	370	80	96
Female	min	46	50	254	224	61	44
	max	69	100	278	299	72	78

SM Table 7.b.: Macronutrients with recommended intake range

Energy and macronutrients (values are calculated based on the reference humans (Table 7.g.))

	Energy (kcal)	Dietary fiber (g)	Sugars (g)	Cholesterol (mg)	Saturated fatty acids (g)
Male					
EFSA	2472	25	32	na	27
HUN	2400	25	32	300	19
Female					
EFSA	1994	25	32	na	22
HUN	1850	25	32	300	14

SM Table 7.c.: Water soluble vitamins

Water soluble vitamins

	Thiamin (mg/d)	Riboflavin (mg/d)	Niacin (NE)	B6 (mg/d)	Folate (µg/d)	B12 (µg/d)	C (mg/d)
Male							
EFSA	1	1,6	16,6	1,7	330	na	110
HUN	1,1	1,6	18	1,3	200	2	90
Female							
EFSA	0,8	1,6	13,4	1,6	330	na	95
HUN	0,9	1,3	14	1,3	200	2	90

SM Table S7.d.: Fat soluble vitamins

Fat soluble vitamins

	A (µg/d RE)	E (mg)	K (µg/d)
Male			
EFSA	750	na	70
HUN	1000	15	na
Female			
EFSA	650	na	70
HUN	800	15	na

SM Table S7.e. Minerals

Minerals

	Calcium (mg/d)	Magnesium (mg/d)	Zinc (mg/d)	Phophorus (mg/d)	Potassium (mg/d)	Iron (mg/d)	Sodium (mg)
Male							
EFSA	950	350	16,3	550	3500	11	na
HUN	800	350	10	620	3500	10	2000
Female							
EFSA	950	300	12,7	550	3500	16	na
HUN	800	300	9	620	3500	15	2000

SM Table S7.f. Mineral ratio

Mineral ratio

	Na:K	Ca:P
Male		
HUN	1:1	2:1
Female		
HUN	1:1	2:1

SM Table S7.g.: Reference humans for nutritional requirement calculations

	Age	**Physical activity level**	**Recommended energy intake**
Reference male			
Dietary quality score$_{HUN}$	average of age group 18-29 and 70+	moderately active	2400 kcal/day
Dietary quality score$_{EFSA}$	average of age group 19-29 and 70-79	moderately active (1.6* basic metabolic rate)	2472 kcal/day
Reference female			
Dietary quality score$_{HUN}$	average of age group 18-29 and 70+	moderately active	1850 kcal/day
Dietary quality score$_{EFSA}$	average of age group 19-29 and 70-79	moderately active (1.6* basic metabolic rate)	1994 kcal/day

SM Table 8. Nutrients as constraints (S_4), (Tompa et al. 2022).

* Constraints were eased when the recommendation was different from the observed intake by +100% or -50%, in which cases, the constraint value equaled to +100% or -50% of the observed intake instead of the RDI. The value of recent intake was based on the publication of HDNSS 2014 (Nagy et al., 2017; Sarkadi Nagy et al., 2017; Schereiberné Molnár, 2017) and affected vitamin D for women and sodium for men. Regarding cultural aspects in this parameter of the model as well, the shift would be too great from observed intake if adhering to the RDIs.

1 HUN = Hungarian specific recommendations (Rodler, 2005; Sarkadi Nagy et al., 2016)

2 FAO/WHO/UNU = World Health Organization (FAO,WHO and UNU 2007)

3EFSA = European Food Safety Authority (EFSA, 2017)

4 FAO and WHO = Food and Agriculture Organization of the U.S. (FAO)/ World Health Organization (WHO) joint recommendation (FAO and WHO, 2008)

5SFA = Saturated fatty acids

6PUFA = Polyunsaturated fatty acids

Nutrient	Unit	Type of constraint	Value	Sex	Source
Energy	kcal/day	max	2000	women	HUN[1]
Energy	kcal/day	min	1700	women	HUN[1]
Energy	kcal/day	max	2600	men	HUN[1]
Energy	kcal/day	min	2300	men	HUN[1]
Protein	share of total energy intake in %	min	15	women	FAO/WHO/UNU[2]
Protein	share of total energy intake in %	min	15	men	WHO[2]
Carbohydrate	share of total energy intake in %	min	45	women	EFSA[3]
Carbohydrate	share of total energy intake in %	max	60	women	EFSA[3]
Carbohydrate	share of total energy intake in %	min	45	men	EFSA[3]
Carbohydrate	share of total energy intake in %	max	60	men	EFSA[3]
Total fat	share of total energy intake in %	min	20	women	EFSA[3]
Total fat	share of total energy intake in %	max	35	women	EFSA[3]
Total fat	share of total energy intake in %	min	20	men	EFSA[3]
Total fat	share of total energy intake in %	max	35	men	EFSA[3]
SFA[5]	share of total energy intake in %	max	10	women	HUN[1]
SFA[5]	share of total energy intake in %	max	10	men	HUN[1]
PUFA[6]	share of total energy intake in %	min	6	women	FAO/WHO[4]
PUFA[6]	share of total energy intake in %	min	6	men	FAO/WHO[4]
added sugar	share of total energy intake in %	max	10	women	HUN[1]
added sugar	share of total energy intake in %	max	10	men	HUN[1]
Sodium	mg/day	min	575	women	EFSA[3]
Sodium	mg/day	max	2400	women	EFSA[3]
Sodium	mg/day	min	575	men	EFSA[3]
Sodium	mg/day	max	3120	men	EFSA[3],*
Fibers total	g/day	min	25	women	EFSA[3]
Fibers total	g/day	min	25	men	EFSA[3]
Calcium	mg/day	min	950	women	EFSA[3]
Calcium	mg/day	max	2500	women	EFSA[3]
Calcium	mg/day	min	950	men	EFSA[3]
Calcium	mg/day	max	2500	men	EFSA[3]

Magnesium	mg/day	min	300	women	EFSA[3]
Magnesium	mg/day	min	350	men	EFSA[3]
Phosphorus	mg/day	min	550	women	EFSA[3]
Phosphorus	mg/day	min	550	men	EFSA[3]
Iron	mg/day	min	16	women	EFSA[3]
Iron	mg/day	min	11	men	EFSA[3]
Potassium	mg/day	min	3100	women	EFSA[3]
Potassium	mg/day	min	3100	men	EFSA[3]
Zinc	mg/day	min	10.1	women	EFSA[3]
Zinc	mg/day	max	25	women	EFSA[3]
Zinc	mg/day	min	12.85	men	EFSA[3]
Zinc	mg/day	max	25	men	EFSA[3]
Vitamin A	µg/RE/day	min	650	women	EFSA[3]
Vitamin A	µg/RE/day	max	3000	women	EFSA[3]
Vitamin A	µg/RE/day	min	750	men	EFSA[3]
Vitamin A	µg/RE/day	max	3000	men	EFSA[3]
Thiamin	mg/day	min	0.9	women	EFSA[3]
Thiamin	mg/day	min	1.1	men	EFSA[3]
Riboflavin	mg/day	min	1.3	women	EFSA[3]
Riboflavin	mg/day	min	1.6	men	EFSA[3]
Vitamin B 6	µg/day	min	1.1	women	EFSA[3]
Vitamin B 6	µg/day	max	25	women	EFSA[3]
Vitamin B 6	µg/day	min	1.5	men	EFSA[3]
Vitamin B 6	µg/day	max	25	men	EFSA[3]
Vitamin B 12	µg/day	min	4	women	EFSA[3]
Vitamin B 12	µg/day	min	4	men	EFSA[3]
Folate DFE	µg/day	min	330	women	EFSA[3]
Folate DFE	µg/day	max	1000	women	EFSA[3]
Folate DFE	µg/day	min	330	men	EFSA[3]
Folate DFE	µg/day	max	1000	men	EFSA[3]
Vitamin C	mg/day	min	95	women	EFSA[3]
Vitamin C	mg/day	min	110	men	EFSA[3]
Vitamin D	µg/day	min	4	women	EFSA[3],*
Vitamin D	µg/day	max	100	women	EFSA[3]
Vitamin D	µg/day	min	5	men	EFSA[3]
Vitamin D	µg/day	max	100	men	EFSA[3]
Vitamin E	mg/day	min	11	women	EFSA[3]
Vitamin E	mg/day	max	300	women	EFSA[3]
Vitamin E	mg/day	min	13	men	EFSA[3]
Vitamin E	mg/day	max	300	men	EFSA[3]

SM Table 9. Absolute and relative change in blue and green water footprint in the alternative dietary scenarios compared to the baseline scenario, by sexes (S_3), (Tompa, Lakner et al. 2020)

Scenarios	**Green water footprint**		**Blue water footprint**	
Male	Value (l/capita/day)	Change in % compared to baseline scenario	Value (l/capita/day)	Change in % compared to baseline scenario
Baseline	2785.6		44.6	
Reduced meat	2602.1	-6.6	41.0	-8.0
Vegetarian	2418.5	-13.2	37.5	-15.9
Vegan	954.7	-65.7	24.5	-45.0
Sustainable	1681.7	-39.6	33.0	-26.0
Cardioprotective	2305.4	-17.2	58.0	+30.1
Ketogenic	3393.2	+21.8	53.8	+20.7
Female				
Baseline	2238.7		36.3	
Reduced meat	2114.0	-5.6	33.9	-6.6
Vegetarian	1989.2	-11.1	31.5	-13.3
Vegan	729.8	-67.4	20.4	-43.8
Sustainable	1257.9	-43.8	24.7	-31.9
Cardioprotective	1724.4	-23.0	43.4	+19.6
Ketogenic	2538.0	+13.4	40.2	+10.9

10.4. Acknowledgements

First of all,

thanks to Zoltán Lakner, my supervisor, whose mentoring was the best kind for me; he has let my bold ideas fall and rise and always provided help and professional guidance when I needed it, as well as, giving me the privilege to share his wisdom with me

and

thanks to Anna Kiss, my academic peer, for being the catalysator of my academic pathway that may have never started and fulfilled without her arranging and managing my "journey" there while she has always been kind and friendly with me

Thanks to the colleagues of the Department of Agricultural Business and Economics, Institute of Agricultural and Food Economics at University of Agriculture and Life Sciences (especially to Ágoston Temesi, Brigitta Plasek, Laura Pfeiffer and Zsuzsánna Bogóné Tóth) for helping me through these 4 years of my PhD with either professional help or just a good talk.

Un grand merci à l'équipe MS-Nutrition de l'été 2021 (en particulier pour Rozenn Gazan, Matthieu Maillot and Florent Vieux) pour l'opportunité de faire un stage dans leur entreprise. En plus de partager l'expertise pour créer mon modèle d'optimisation de l'alimentation durable, ils m'ont également fait découvrir la culture française et les côtes de Marseille que je garde comme une expérience profondément précieuse.

Köszönöm szüleimnek, akikkel kezdődött ez a történet; anyámnak Fazekas Gabriellának és párjának Onódi Ákosnak és apámnak, Tompa Ádámnak és feleségének Tompa Ádám Jánosné Somodi Edinának, hogy kitartóan és türelmesen támogatták a tanulmányaimat, ami különösen a gimnáziumi éveim alatt egy hullámvasút volt. Ákosnak, a mindennapokban nyújtott segítsége mellett, külön köszönet a sok beszélgetésért a világ működésével kapcsolatban, amit a próbálkozás ellenére még nem tudtunk megfejteni.

Thanks to T. M. 🦔, my love, for providing me a case study as solid evidence for what it's worth; always seeking true passion and love and never settling for „good enough" in any aspect of life, neither do in scientific work.

Thanks to my friends, Réka Pecz and Nóra Pfaff and for being my chosen family and being there for me both at bright and grave times.

Thanks to Ana Raner, my friend, for our priceless and never-ending conversation about the nature of the inner and outer world, including, quite often, science as our great interest

Thanks to Csaba Orbán Ph.D. for sharing his profound passion and knowledge of science with me; one of his fellow students desperate to learn the way of things.

Thanks to Barbara Biró and Zsanett Bodor, my academic peers of 10 years who have always put the standard so high and never hesitated to help me through my university years.

Thanks to Zoltán Magyarovits, who professionally and kindly helped me to finish my swimming career as I deserved it, at the top, so that I could start my academic path with a light heart.

Thanks to Viktória Faludi, my former psychotherapist, who was the first one to make me believe that my intellect is also worth besides my athlete performance and that asking the question is not a bad thing after all.

Thanks to the teaching staff of Sashegyi Arany János Primary and High School (in the school year of 2009/2010), who took me in their school despite my failing grades and lack of motivations and managed to give me back the joy of studying, thus leading me to "good enough" high school finals exam to continue my academic pathways.

Thanks to the teaching staff of Szent István Elementary School (in the school years of 1998-2006) for teaching me so well for the very basis of everything and creating a memory of my "alma mater" as good as it can be.

Thanks to Gömböc, my British shorthair cat, who witnessed and supported - with an infinite supply of purring - my academic journey from the very beginning, since 10 years.

At last, but not least, the unavoidable limitations,

Thanks to those of my swimming coaches who kept saying that I am dumb because of my inclination to overthinking, asking questions, and not just surrendering without doubts and who regarded school as a wrong excuse for swimming practice. Also, thanks to those of my teachers who kept telling me that I will get nowhere in the academic world and regarded swimming practice as a wrong excuse from school. Well, they were neither excuses nor wrong.