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Preface

This volume contains edited papers presented at the 13th International Conference on Sustainable Development and Planning, organised by the Wessex Institute of Technology (WIT). This event took place in Seville, Spain from 23 to 25 September 2024.

The contributors to this volume addressed problems related to development and planning, affecting urban and rural areas, and encountered in many regions of the world. Accelerated urbanisation has resulted in the deterioration of the cities' environment and loss of quality of life. Developing new methodologies for monitoring current conditions as well as planning and implementation of novel mitigating strategies can offer solutions towards reducing pollution and the non-sustainable use of available resources.

Energy-saving and eco-friendly building designs have become an important part of modern development, which places special emphasis on increasing efficiency and reducing emissions. Planning has a key role to play in ensuring that such approaches, as well as new materials and processes, are implemented in the most effective manner.

Sustainability in the built environment is a broad area of study covered extensively in this volume with articles dealing with urban planning and design, shared and green spaces as well as sustainable building practices. The impacts on the environment are examined in the contexts of tourism, air pollution and greenhouse gas emissions, diesel to electric mobility transition as well as energy, sugar and bicycle helmet production.

Management strategies for wetlands and national forests, drought, water scarcity and desalination, seawater intrusion are some of the issues discussed under natural resources management.

Public views, the stock market as well as multidisciplinary dimensions and elements of green logistics are explored as the basis for possible sustainable development indicators. The analytic hierarchy process is applied to bridge the gap between aquavoltaics policy planning and stakeholder expectations. It is suggested that expressway construction has a moderating effect on environmental governance and sustained environmental, social and governance performance has an influence on corporate financial performance; also, that the sanctioning process in mining legislation can be strengthened by stakeholders' engagement.

The volume also includes plenty of informative and topical material in the areas of sustainable mobility, energy efficiency, community and city planning, rural areas development, waste management, quality of life as well as the carbon and ecological footprint.

Two special sessions were held at the conference. The subject matter of the first was strategies for environmental sustainability with focus on waste collection, treatment and disposal as well as environmental performance and practices in higher education institutions, in particular. The second special session was dedicated to energy-climate transition through transnational municipal cooperation. Papers from this session deal with adaptation planning for addressing climate change in urban environments as well as local and national authorities' strategies for clean energy transition.

These papers, like others presented at WIT conferences, are uploaded to CrossRef and appear regularly in suitable reviews, publications and databases, including referencing and abstracting services. They are also archived on-line in the WIT eLibrary (<http://www.witpress.com/elibrary>) where they are permanently available in Open Access format to the international scientific community.

The Editor wishes to thank the members of the International Scientific Advisory Committee who have peer-reviewed the submitted papers. Special thanks go to the Conference Coordinator, Ms Marta Graczyk, WIT's IT Manager, Mr Alan Morgan, and WIT Press Production Manager, Helen Hill, for their significant contribution to the success of the conference and the processing of papers for publication in these Transactions.

Stavros Syngellakis

The Editor, 2024

Contents

Section 1: Sustainable development indicators, governance and policies

Public views on sustainability issues over a 33-year period in Idaho, USA <i>Robert L. Mahler & Nav Ghimire</i>	3
Analysis of the relative performance of clean energy stock indices <i>Niyazi Berk, Dina Cakmur Yildirtan & Selin Sarili</i>	17
Addressing the wicked problem of energy policy: A data-driven approach using the analytic hierarchy process in aquavoltaics policy of Taiwan <i>Chia-Ling Lee, Sheng-Xiang Kao & Chien-Te Fan</i>	33
The moderating effect of expressway construction on environmental governance: Evidence from China <i>Zixuan Zhao, Kunhui Ye & Yuyao Liu</i>	47
The influence of sustained ESG performance on corporate financial performance <i>Zhaokun Guo & Kunhui Ye</i>	55
Stakeholders' engagement to strengthen the sanctioning process in the mining legislation of Ecuador <i>Mauricio Murillo, Yajaira Andrade Torres, Fernando Morante-Carballo, Maribel Aguilar-Aguilar & Paúl Carrión-Mero</i>	69
Multidisciplinary dimensions and elements of green logistics as a basis for the development of a regional sustainability indicator <i>Gloria Janeth Murillo-Aviña, Josué Aarón López-Leyva, Carlos Sergio Robles-Mejía, Sialia Karina Mellink-Méndez, Diana Esther Woolfolk-Ruiz & Ana Lucía Negrete-Elizondo</i>	81

Section 2: Energy efficiency

How to enhance the uptake energy efficiency measures identified in the audits for industrial companies: The AUDIT2MEASURE project <i>Simone Maggiore & Stefano Moscarelli</i>	95
---	----

Could Russian hydropower projects reach economic efficiency? Justification of possible scenarios <i>Galina Chebotareva</i>	105
--	-----

Experimental analysis of heat transfer in soil at different water table levels <i>Sandeep Bandarwadkar & Tadas Zdankus</i>	117
---	-----

Section 3: Sustainability in the built environment

Towards sustainable cities: Flora grown and traded in Salvador, Brazil <i>Isabel Maria Madaleno</i>	129
--	-----

A new perspective on urban architecture: Streets above ground for better adaptation with nature <i>Dmytro Legeyda</i>	141
---	-----

Measuring uncertainty: Facing place mutations sustainably <i>Marichela Sepe</i>	155
--	-----

Energy retrofitting of heritage protected university buildings: An interoperability challenge <i>David Bjelland & Bozena Dorota Hrynyszyn</i>	165
---	-----

Human-centred urban design: Small interventions, big impact for habitable cities <i>Marta Rodriguez</i>	177
---	-----

A case study on housing location guidance in a compact city in Sapporo, Japan <i>Nobuo Kawahara</i>	187
---	-----

The role of shared space fostering cooperation towards sustainable wellbeing in urban communities: The representative case of the Genova community in Freiburg, Germany <i>Marina Montelongo & Udo Dietrich</i>	199
--	-----

Integration of affordable housing and green residential building design in the construction sector in Cambodia <i>Makara Long, Virak Han, Pierre Leclercq & Sigrid Reiter</i>	215
---	-----

Step-by-step method for district renovation through community engagement and urban planning to foster local economic development and improve the quality of life <i>Olatz Nicolas Buxens, Silvia Urrea-Urriarte, Amaia Sopedana, Itsaso Gonzalez Ochoantesana & Idoia Landa Oregi</i>	229
--	-----

Sustainable spatial planning for rural–urban fringes: A case study in Turkey <i>Tolga Levent</i>	243
Sustainable design strategies in architectural construction, focusing on biomaterials and their applications for the goals of the 2030 Agenda <i>Christina Dikou & Nikolaos Kourniatis</i>	255
Unlocking green knowledge transfer: Cell biology insights for sustainable exchange in engineering projects <i>Yao Zhang, Kunhui Ye & Beifei Yuan</i>	267
The Matteotti village by Giancarlo De Carlo: Participatory architecture before and after the Millennials <i>Francesco Demma, Alessio Patalocco & Sara Massarini</i>	277
Modelling and factor analysis of building lot consolidation in built-up areas <i>Toshihiro Osaragi & Takeshi Inoue</i>	289
Seismic and structural risk assessment of an educational building for community sustainability: A case study in Zaruma, Ecuador <i>Josué Briones-Bitar, Pedro P. Rojas, Cindy Moya, Martha Caballero, Wilmer Márquez, Paúl Carrión-Mero & Fernando Morante-Carballo</i>	303

Section 4: Sustainable mobility

Contradictions around the formalisation of South Africa’s minibus taxi industry <i>Siyabulela Christopher Fobosi</i>	319
Characterising major storm event impacts on rural routes <i>Thomas M. Brennan Jr, Andrew J. Bechtel & Mohan Venigalla</i>	327
Towards sustainable development: Exploring the optimal strategy for promoting new energy vehicles within the 2030 carbon emission reduction target in China <i>Yuyao Liu, Kunhui Ye & Zixuan Zhao</i>	339
Hydrogen mobility for Qatar: A comparison between conventional, electric and hydrogen fuel cell vehicles using life cycle cost analysis <i>Carlos Méndez, Brenno Castrillon Menezes, Marcello Contestabile & Yusuf Biçer</i>	347
Ride-hailing in Indian cities: Using interviewee quotes to develop a research agenda for sustainable mobility <i>David Ashmore, Parul Sharma & Branislava Godic</i>	353

Green light optimal speed advisory with reduced default speed:
Analyses of a new GLOSA service
Maik Halbach 367

Sustainable development through strategic road safety management:
A regional approach
Miroslava Mikusova, Kyandoghere Kyamakya & Jozef Gnap 379

Section 5: City and community planning

Putting urban poverty back on the urban policy agenda:
Upgrading an unplanned settlement in Beira, Mozambique
Corrado Diamantini, Susanna Ottaviani, Livia Serrao, Alfredo Manhota Antonio, Amerigo de Stela Vladimir Msopela, Harold Juvenal Chate & Guido Zolezzi 393

Planning and recordation of heritage conservation in the tropics:
Piloting digital preservation of La Mina Recreation Area, Puerto Rico
Raymond Feliciano & Johnny Lugo-Vega 405

Marketplace mosaics: Understanding the inner mechanisms of newly
emergent informal street markets in Colombo, Sri Lanka
Randima De Silva & Prasanna Divigalpitiya 417

Singularity as a principle in urban development process
Amr Sharaby 429

Section 6: Rural areas development

Co-designing interventions to create awareness and reshape the future
in a Mexican semiarid agricultural community
Emanuele Giorgi, Tiziano Cattaneo, Lina Carreño, Alfredo Mauricio Flores Herrera & Emiliano Chavez 441

Integrated rural development and environment issues in Indonesia:
Is the quintuple helix model sustainable?
Ida Widianingsih, Abdillah Abdillah, Qinthara Mubarak Adikancana, Ahmad Zaini Miftah, Anggia Utami Dewi & Risna Resnawaty 451

Review of agricultural cadastre approaches using geomatics for rural
development
Paulo Escandón-Panchana, Sandra Martínez-Cuevas, María Jaya-Montalvo & Gricelda Herrera-Franco 465

Decision-making tools for sustainable recovery of rural villages:
Planning policies and implementation strategies for valorising small
communities in inner areas under the next generation EU programme
Stefano Bigiotti, Carlo Costantino & Alvaro Marucci 479

Section 7: Waste management

Waste-to-energy strategy concept for a coal-firing power plant in the Czech Republic: Part A – Waste co-incineration approach <i>Marie Molinková, Jiří Ryšavý, Radim Kovařík, Silvie Purmanská & Jakub Čespiva</i>	497
Waste-to-energy strategy concept for a coal-firing power plant in the Czech Republic: Part B – Waste gasification/pyrolysis approach <i>Marie Molinková, Jiří Ryšavý, Radim Kovařík, Silvie Purmanská & Jakub Čespiva</i>	511
Integration of remote sensing technologies within decision support systems for the enforcement of illegal dumping: Principles and numerical simulations <i>Luca Cicala, Donato Amitrano, Sara Parrilli & Cesario Vincenzo Angelino</i>	525
Obtention of activated carbon by reutilisation of oil palm residues: A circular economy case study <i>Fernando Morante-Carballo, Luis Zambrano-Chiliquinga, Carlos Robalino-Jara & Jairo Dueñas-Tovar</i>	533
Mathematical modelling of a binary system of copper and lead biosorption in a fixed bed column <i>Felicia Omolara Afolabi & Paul Musonge</i>	545

Section 8: Natural resources management

The intersection of Agenda 2063 (Goal 11) and Sustainable Development Goal 6: Exploring the ‘harder’ obligations for wetland management strategies in selected African countries <i>Bramley J. Lemine, Chesnè Albertus, Bongani Ncube, Thokozani Kanyerere & Mahabubur Chowdhury</i>	561
Integration of water desalination systems on electrical microgrids for remote coastal communities <i>Rafael Omar Batista, Ruben Dario Ramos Ciprian, Nestor Francisco Guerrero, Jose Miguel Salavert & Idalberto Herrera Moya</i>	571
Assessment of the stakeholder engagement and monitoring stages in the adaptive management of a national forest in western Colorado, USA <i>Jordan Truitt, Rafael Moreno-Sanchez & Calvin Speas</i>	581

Addressing water scarcity in the Magdalena department, Colombia: A comprehensive analysis using system dynamics and Bourdieu's theory <i>Miguel A. De Luque-Villa, Natalia Carrillo-Acosta, Ana Carolina Douglas-Quinto, Martín Otálora-Low & Mauricio González-Méndez</i>	599
Drought trends in a coastal region with complex topography in northern Colombia <i>Eucaris Estrada & Heli A. Arregocés</i>	609
Design and creation of a database to assess the information needs of hydrological models <i>Luis Izquierdo-Horna, Jose Zevallos, Thurian Cevallos & Daniela Rios</i>	619
A systematic review of geophysics applied in seawater intrusion research <i>Joselyne Solórzano, Emily Sánchez-Zambrano, Maribel Aguilar-Aguilar, Astrid Ramírez-López, Eudes Ramos-Sánchez, Milena Baque & Paul Carrión-Mero</i>	631
 Section 9: Environmental impacts	
Carrying capacity assessment in tourism: The case of Mykonos Island, Greece <i>Dimitris Prokopiou, Georgios Mavridoglou & Theodora Giantsi</i>	647
The urban street as a pollution hot-spot: Simulations and measurements for model evaluation <i>Alfred Micallef</i>	657
Influence on air quality of moving from diesel to electric buses: The case of the city of Cuenca, Ecuador <i>Rene Parra, Claudia Espinoza, Cristian Caguana & Emilio Heredia</i>	669
Sustainable development analysis in the sugar industry: Assessing environmental energy impact in sugar production through lifecycle assessment <i>Diana Carolina Cedano, Ruben Dario Ramos Ciprian, Maria J. Bastante & Rosario Viñoles</i>	683
Analysis and observations concerning concentrations of greenhouse gases measured over an 11-year period in the central Mediterranean region <i>Martin Saliba & Alfred Micallef</i>	693
Some observations on measurements of background concentrations of atmospheric black carbon and sulphur dioxide in the central Mediterranean region <i>Rebecca Caruana & Alfred Micallef</i>	705

An auditing framework and checklist to guide green IT assessment in businesses <i>Evangelia Kopanaki & Dimitrios S. Stamoulis</i>	717
Exploring environmental impacts in the bicycle helmet market: A life cycle assessment approach <i>Luis Silva, Bruna Machado, Pedro Sá, Bruno Silva & Natália Ladeira</i>	727
Environmental assessment of quarrying in volcanic islands: The case of ‘Cerro Quemado’, Galapagos, Ecuador <i>Jairo Dueñas-Tovar, Fernando Morante-Carballo, Emely Loor-Medranda, María Jaya-Montalvo & Paúl Carrión-Mero</i>	739
Improving the procedure of environmental audit at traditional energy enterprises <i>Anzhelika Karaeva & Elena Magaril</i>	751

Section 10: Quality of life

Nutritional life cycle assessment: A paradox or a pathway to sustainable agro-food systems? <i>Valentina Niccolucci, Cosimo Montefrancesco, Roberta Russo, Elisa B. P. Tiezzi & Nadia Marchettini</i>	763
Impact of airborne microplastics on induced sputum of urban dwellers: The role of environmental and occupational factors <i>Javier Bayo, Carlos Baeza-Martínez, Marta Doval, Miguel González-Pleiter & Eduardo García-Pachón</i>	775
Forest fires as a public health challenge in Chile: The case of the Biobío region <i>Valeria Scapini, Martín Del Barrio & Alfredo Pizá</i>	787

Section 11: Carbon and ecological footprint

Carbon and environmental footprint of cities and communities: A Living Labs experience <i>Carlo Trozzi, Erika Brattich, Muhammad Adnan, Enzo Piscitello, Francesco Barbano, Carlo Cintolesi, Rita Vaccaro, Silvana Di Sabatino & Antonio Parodi</i>	799
Environmental footprint of diesel fuel in the shipping sector <i>Maja Perčić, Tatjana Haramina, Vladimir Soldo, Marilena Demetriou & Nikola Vladimir</i>	811

Assessing energy-saving retrofit and carbon footprint reduction of rural dwellings: A case study in Tuscia, Italy
Carlo Costantino, Stefano Bigiotti & Alvaro Marucci 821

Analysis of Shah Alam’s carbon emissions based on Malaysia’s low carbon city framework and assessment
Azlin Mohd Azmi, Mohd Hanif Mohd Ramli, Hairi Ponichan & Halimatun Mohd Yunus 835

Section 12: Energy–Climate transition

Empowering local authorities to accelerate the clean energy transition: The LOCAL GoGREEN project
Monica Salvia, Cveta Dimitrova, Luigi Santopietro, Benjamin Hueber, Carmelina Cosmi, Filomena Pietrapertosa, Edita Pajaziti, Ivana Mikulic, Uli Jakob, Elis Vollmer, Lenard Milich, Beatriz Soler & Roman Kekec 847

Transition management fostering sustainable pathways for local authorities toward a liveable future: A case study of Ravenna, Italy
Paola Clerici Maestosi & Michela Pirro 859

New greenhouse gas simulation and mapping tools to support local carbon neutrality agendas: A case study of the city of Almada, Portugal
Filipa Amorim, Sofia Simões, Juliana Barbosa, Paula Oliveira, Paula Trindade, Laura Aelenei, Justina Catarino, Susana Viana & Leonor Figueiredo 873

The CapaCITIES project to support national government engagement and stimulate transnational cooperation: The role of ambassadors as facilitators for the dissemination of national platforms
Monica Salvia, Paola Clerici Maestosi, Filomena Pietrapertosa, Michela Pirro, Luigi Santopietro & Gilda Massa 885

Sustainable integrated urban planning as resilient knowledge building: Narni (Italy) and the LIFE IN-PLAN project
Alessandra Alessandrelli, Filippo Canneta, Valentina Francescangeli, Filippo Andrea Rossi, Alessandra Trionfetti, Fabrizia Salvi & Marco Slavich 899

The urgent call for tangible actions to adapt regions to climate change impacts: The example of IMPETUS mountain demonstration site
Valentina D’Alonzo, Valentina M. Cittati, Eleonora Leonardi, Silvia Cocuccioni, Liz J. Olaya Calderon, Petra Pagliughi, Matteo Rizzari, Giorgia Robbiati & Nicolò Franceschetti 909

NUTRITIONAL LIFE CYCLE ASSESSMENT: A PARADOX OR A PATHWAY TO SUSTAINABLE AGRO-FOOD SYSTEMS?

VALENTINA NICCOLUCCI¹, COSIMO MONTEFRANCESCO¹,
ROBERTA RUSSO¹, ELISA B. P. TIEZZI² & NADIA MARCHETTINI¹

¹Ecodynamics Group, Department of Earth, Environmental and Physical Sciences, University of Siena, Italy

²Department of Information Engineering and Mathematics, University of Siena, Italy

ABSTRACT

A comprehensive sustainability assessment of food products requires a framework that effectively captures the complex interplay between nutritional value and environmental impact, encompassing both planetary-health and human well-being. This dual focus is becoming increasingly relevant: it can happen that foods with exceptional nutritional benefits may still come with substantial environmental costs. Conversely, foods with lower environmental impacts might not offer optimal nutritional value. The challenge, therefore, is to achieve a balance between consuming foods that are both healthy and sustainable. Despite the extensive literature on the environmental impacts of food production and consumption – often assessed through life cycle assessment (LCA) – there remains a notable gap in integrating nutritional aspects into these evaluations. This paper aims to address this gap by exploring the application of nutritional life cycle assessment (n-LCA), an emerging tool designed to incorporate nutritional information into the traditional LCA framework. Given its novelty, this paper discusses both the potential benefits and limitations of n-LCA. A practical case study from a specific food group is presented to support this discussion, particularly in terms of selecting the most appropriate functional unit and highlights the importance of utilising such tools. The findings suggest that n-LCA provides a more holistic framework for evaluating food system sustainability, offering a deeper understanding of the trade-offs between health and environmental sustainability, and thereby facilitating more informed decision-making in food production and consumption.

Keywords: agri-food products, life cycle assessment, nutritional life cycle assessment, sustainable production, human and planet health, carbon footprint.

1 INTRODUCTION

Agriculture is a predominant economic sector in most nations worldwide, serving as a major consumer of natural resources and, consequently, as a significant contributor to environmental degradation. Over the past few decades, substantial efforts have been made to quantify these environmental impacts. Current estimates reveal critical associations, attributing 30%–40% of global contributions to climate change, 70% of freshwater consumption, 30% of primary energy use, and 30% of habitat loss to agricultural activities, which is a major driver of biodiversity decline [1], [2]. At the same time, the escalating global population necessitates increased agricultural production, thereby intensifying the environmental costs [3].

One of the greatest challenges of the coming decades is meeting the global nutritional demand while safeguarding the environment and reducing pressure on food resources [4]. In this context, accounting tools such life cycle assessment (LCA) play a fundamental role [5]–[7]. It provides a robust framework for understanding the environmental implications of agri-food products, identifying key areas of environmental concern and potential trade-offs, and supporting the development of strategies to mitigate negative impacts and improve overall performance [6]–[10]. One notable advantage of LCA is its ability to identify



potential burden shifts between different life cycle stages and environmental impact categories [4], [11].

Traditional LCA is primarily focused on purely environmental aspects, documenting the health and state of the environment by analysing various indicators such as climate change, resource depletion, acidification, ozone depletion, and other relevant topics [11]. While this approach offers a comprehensive understanding of how different stages of a product's life cycle can affect environmental integrity, it does not account for the primary function of food – its nutritional value and health implications. This gap in traditional LCA methodologies underscores the need for complementary approaches, such as nutritional LCA (n-LCA), which aims to integrate nutritional parameters into the environmental assessment framework [12]–[17].

In the context of the agri-food sector, the primary biological function of food consumption is to meet the essential nutritional needs of the human body. This fundamental role has been articulated in various ways within the literature. For example, Cucurachi et al. [6] describe it as the ability to 'satisfy the need of the human body to be nourished', while other authors discuss food's role in 'inducing satiety' [18], both emphasising the importance of food in fulfilling basic physiological requirements. Similarly, Kyttä et al. [19] highlight this function as 'the adequate intake of energy and nutrients to maintain bodily functions and health' underscoring the necessity of a balanced diet to support overall well-being. McLaren et al. [20] concisely refers to this function as 'providing nutrients' capturing the essential role of food in delivering the vital substances required for growth, maintenance, and health. Moreover, food consumption patterns vary widely based on geography, gender, age, culture, customs, and social status, among other factors.

This paper offers an insight on the topic of n-LCA methodology highlighting its key features and its potential to address the complex challenge of balancing global nutritional demands with environmental resources supply.

Moreover, a detailed overview of the most suitable and informative functional units and impact categories for n-LCA studies is proposed. The importance of selecting appropriate functional units – whether mass-based, energy-based, or nutrient-specific – is emphasised, as these choices significantly influence the outcomes of LCA assessments, underscoring the need for careful consideration to ensure the accuracy and relevance of the analysis. Similarly, the selection of impact categories must be meticulously chosen to capture the full spectrum of sustainability considerations relevant to food systems.

To contextualise and support the theoretical discussion, this study includes an in-depth analysis of the 'oils and fats' food group. This empirical example demonstrates how n-LCA can be applied to evaluate the sustainability of different food systems. The ability to provide a nuanced understanding of how food production and consumption impact both planetary health and human well-being is essential, even though much progress is still needed in this topic.

The results presented in this paper were developed within the framework of the AGRITECH project, which is part of the Italian National Recovery and Resilience Plan (PNRR). This project focuses on a comprehensive evaluation of environmental, social, and economic impacts within food production chains. The primary aim is to enhance the sustainability of agricultural practices and food production by integrating innovative technologies and methodologies designed to assess and mitigate adverse impacts. In doing so, the project seeks to address the complex challenges associated with sustainable food systems, promoting practices that not only look at reducing environmental impacts but also include other perspectives such as economic and social, with a look also at the nutritional aspects.



2 MATERIAL AND METHOD

n-LCA represent a novel advancement of the traditional LCA aimed to provide a more holistic evaluation that goes beyond environmental impact, considering the nutritional value and its implications for human health [20]–[24]. A simplified workflow for n-LCA adapted from McAuliffe et al. [24], is illustrated in Fig. 1. This workflow outlines the fundamental steps involved in conducting an n-LCA, providing a streamlined overview of the process from defining the goal and scope of the study to interpreting the results. The iterative sequence for traditional LCA is reported in black lines, while the specificities for n-LCA are depicted in grey lines.

The figure serves as a guide for understanding how different stages of the n-LCA framework interact, highlighting the importance of accurately defining functional units, selecting appropriate impact categories, and systematically collecting and analysing data to assess the environmental impacts of food products based on their nutritional contributions. At least two key aspects, closely interconnected, are worth discussing in detail: the selection of the most relevant and informative functional unit(s), and the choice of the impact assessment methodology [20], [24].

The choice of the most appropriate and meaningful nutritional functional unit(s) (n-FU) is a critical step in the n-LCA [20], [21], [23]–[26] and is included in phase 1. Its selection is influenced by several factors, including the specific characteristics and intended primary function of the product, the nutritional requirements of the target population, and the overarching objectives and scope of the study. A well-chosen n-FU ensures that the analysis aligns with the true function of the product. Additionally, a clear and appropriate n-FU facilitates consistency in data collection and interpretation, which is essential for obtaining reliable and comparable results.

To date, there is neither a consensus nor standardised guidelines on the most reliable n-FU, even if some guidance on selecting it have been provided [20]. The literature presents various approaches, each with its own advantages depending on the context and goals of the study as well if the impact assessment is mid- or end-point. Typical examples of mid-point n-FUs are based on the *quantity or volume* of food, as outlined in ISO 14044 [27] and supported by several authors [9], [20].

These n-FUs, which are commonly expressed in terms of mass (e.g., kilograms) or volume (e.g., litres), provide a straightforward and widely applicable basis for comparing different food products. Such FU is particularly recommended in the ENVIFOOD Protocol [28]. The limit of this n-FU is that do not include nutritional information and do not look at the substitutionally of food.

Another widely recognised n-FU is the *servicing size*, which reflects a standard portion size such as one banana or one cup of wine. Alternatively, the *average daily intake*, such as the recommended dietary allowance (RDA), offers a more individualised FUs based on nutritional recommendations. Poore and Nemecek [4] highlight these approaches as meaningful ways to evaluate food products, as they align more closely with actual consumption patterns and dietary guidelines. These are dependent to recommended doses and may change for different countries.

In addition to these quantity-based n-FUs, functional units can also be defined on a nutrient basis. This approach accounts for the *nutritional content* of food products, focusing on specific macronutrients (e.g., grams of protein) or micronutrients (e.g., milligrams of essential vitamins such as vitamin C or B12). Alternatively, *calories* (kcal) can serve when the primary concern is energy intake. Protein content is the widest used n-FU, even if some worries about its effectiveness are acknowledged [20], [21], [24]. Some authors suggest using *quality adjusted protein*, to take into consideration the quality of the proteins [20], [21], [24].



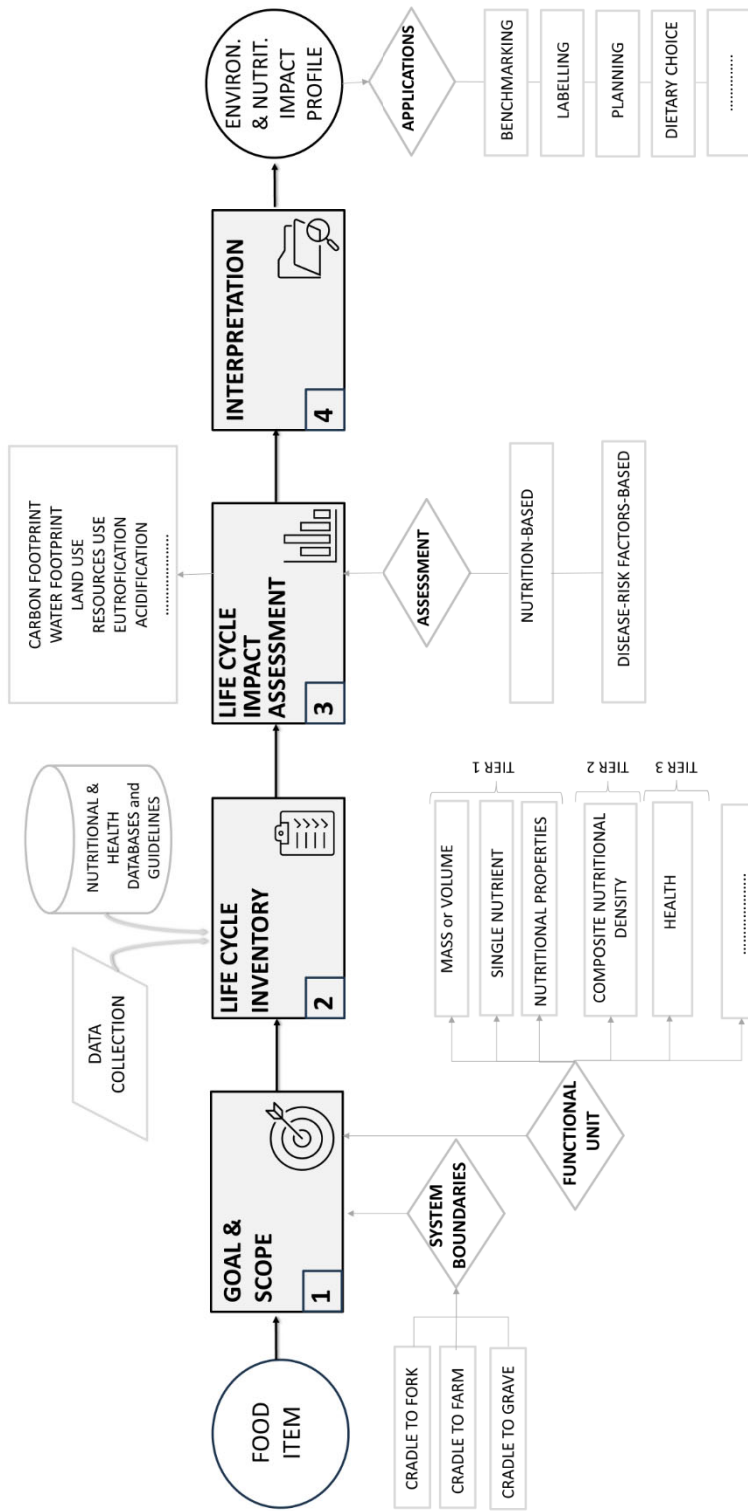


Figure 1: Workflow for n-LCA. (Source: Adapted from McAuliffe et al. [24].)

n-FU can be designed to capture a broader spectrum of a food product's attributes by incorporating a combined scoring system that weighs both beneficial and detrimental nutrients. It can be designed also to reflect more than a single aspect of a food product through combined score weighting measures of qualifying and/or disqualifying nutrients. One notable example of a multi score FU, among others, is the well-established *nutrient rich food (NRF) index* [29], specifically the NRF9.3 score and its variants. This scoring system evaluates the nutritional content of food products on the basis of the content of nine nutrients to encourage – protein, fibre, vitamins (A, C, D), minerals (calcium, iron, potassium, and magnesium) – while simultaneously accounting for three nutrients to limit – saturated fatty acid (SFA), added sugar, and sodium. The NRF9.3 score provides a comprehensive measure of a food product's overall nutritional quality, balancing the benefits of essential nutrients with the potential risks associated with overconsumption of certain detrimental components. By combining multiple nutritional factors into a single score, the NRF9.3 and similar indices can serve as effective tools for comparing the healthfulness of different foods, thereby helping to identify options that are both environmentally sustainable and nutritionally beneficial. On the other side, this n-FU is a more complex and harder to understand than others.

Another interesting proposal for a suitable n-FU is a product-group-specific nutrient index especially for protein-rich foods [19].

Alternative n-FUs are oriented towards the consequences of nutrition on human health (for example using disability-adjusted life years (DALY)). Despite its great potential, it is particularly complex, too aggregated and therefore not always easy to interpret [18].

The impacts profile generated by LCA can be categorised as (i) nutrition based (mid-point type) or (ii) disease-risk factors-based (end point type) [13], [14], [20], [24]. The first class is focused on the nutritional value of food, based on the content of individual nutrients or metric describing nutritional quality based on several nutrients. Mid-point indicators focus on the observation and quantification of changes in the natural environment caused by emissions or resource use due to the production of that product. These indicators are often easier to calculate and understand as they are closer to the source of the impact and less affected by uncertainties and assumptions. However, they may not capture the full consequences of environmental changes for human well-being or ecosystem services and may not reflect the relative importance or severity of different impact categories. The second group analysed the dietary health effects, for example by using health metrics to estimate the dietary impact on a specific health outcome. End-point indicators, on the other hand, are oriented towards the final damage or benefit to human health, natural resources, or biodiversity caused by emissions or resource use. Although these indicators are often more relevant and comprehensive as they show the ultimate outcomes of environmental changes, they may be more difficult to calculate and interpret. This complexity arises because end-point indicators require more data and modelling and involve more uncertainties and value judgments.

3 RESULTS AND DISCUSSION

3.1 SWOT analysis

The n-LCA is becoming a powerful impact assessment tool capable of addressing the complexities inherent in evaluating the sustainability of food systems and offering new and important perspectives. Through the framework of SWOT analysis, the current state of the methodology is analysed, and the relative results are presented in Fig. 2. By systematically



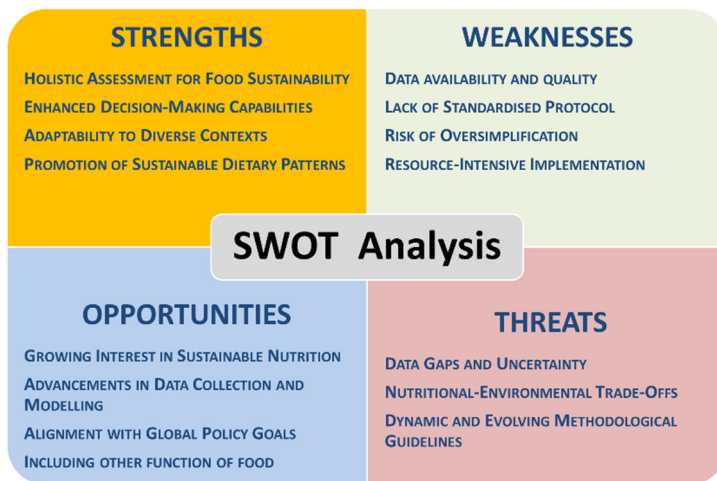


Figure 2: The SWOT analysis that summarises the main strengths and weaknesses, with opportunities and threats for n-LCA.

evaluating strengths, weaknesses, opportunities, and threats, the SWOT analysis provides a comprehensive understanding of how the methodology can be optimised for more effective application in various contexts.

Despite its recent introduction, the ‘dual lens’ approach of the n-LCA – considering not only the environmental impact but also the contribution to human nutrition and well-being – is the highlight of this method. This results in a more comprehensive and holistic sustainability assessment of food systems. The framework is adaptable and flexible, allowing it to be customised for specific food products, dietary patterns, or regional contexts, making it more relevant and applicable. This contributes to promoting sustainable dietary patterns. Overall, n-LCA facilitates informed decision-making for policymakers, producers, and consumers by identifying management strategies that optimise both environmental and nutritional outcomes, thus preventing the transfer of burdens among them.

On the other hand, there are several weaknesses that need to be addressed in order to make the n-LCA more robust and affordable. Reliability depends on the availability and accuracy of data: an extensive and detailed nutritional and environmental dataset is required. While this aspect is recommended, its high complexity can often be a deterrent to its use. The absence of a universally accepted standardised protocol for n-LCA can lead to variability in outcomes, reducing the comparability and reliability of results. Additionally, integrating complex nutritional and environmental information into a single assessment may oversimplify things, and caution must be exercised. It is recognised that LCA-based frameworks are all resource-intensive and require significant investments in time, financial resources, and expertise, which may limit their widespread adoption. Certainly, n-LCA presents important challenges. It increases and stimulates global interest in sustainable diets and can support international policy initiatives aimed at improving nutrition and reducing environmental impacts, aligning with the Sustainable Development Goals (SDGs). Furthermore, advancements in data collection, processing, and modelling can improve the precision and efficiency of n-LCA, making it more accessible and reliable. Gaps or uncertainties in data can compromise the robustness of the analysis. Similarly, the perceived complexity, cost, and resource requirements may lead to resistance from stakeholders,

hindering widespread implementation of n-LCA. n-LCA could reveal trade-offs between nutritional quality and environmental impact, posing challenges in balancing these aspects and making difficult decision-making scenarios. It should not be underestimated that the continuous evolution of dietary and environmental guidelines requires regular updates to n-LCA methodologies, which may introduce challenges in maintaining consistency and comparability over time.

The findings of this analysis underscore that n-LCA emerges as one of the most compelling indicators and metrics available in literature for evaluating sustainability within the agro-food sector. Given its potential to advance our understanding of sustainable food systems, further exploration and refinement of the n-LCA methodology are highly warranted. Enhancing the accuracy, relevance, and applicability of n-LCA will be crucial for developing a more effective tool and committed to fostering sustainable agricultural practices and improving public health outcomes.

3.2 The selection of n-FU: the case study of oils and fats food groups

The selection of an appropriate n-FU is a pivotal aspect of the n-LCA, as it significantly affects the analysis's outcomes. As highlighted in the previous paragraph, the complexity of this decision is amplified by the complexity inherent in the research question and the desired analytical outputs. Currently, there is no universally accepted standard for determining the most suitable n-FU across all food categories. Recognising that food items can generally be grouped into relatively homogeneous groups based on the key nutrients they provide, a feasible approach could involve proposing food group-specific n-FUs accordingly also to other papers [19]. The underlying rationale is to underscore the nutritional value inherent in each food group, reflecting the primary reasons for their consumption, without accounting for any potential negative impacts. Moreover, this method emphasises the substitutability of products within the same category. By aligning the n-FU with the specific characteristics and functions of each food group, this method enhances the relevance and precision of the n-LCA, ultimately contributing to more informed decisions in food production and consumption.

To illustrate the significant role of selection of the FU and make it more explicit, the 'oils and fats' food group was considered. This category plays a crucial role in human nutrition and includes both plant-based oils and animal-derived fats. These dietary fats provide essential calories for energy and facilitate the absorption of fat-soluble vitamins (i.e., E, A, and D). Beyond their nutritional value, dietary fats serve important physiological functions, such as protecting vital organs, regulating body temperature, and contributing to overall health. The fundamental components of oils and fats are fatty acids, which are categorised into two primary types: unsaturated and saturated. Unsaturated fatty acids, which are liquid at room temperature, include both monounsaturated and polyunsaturated fats. In contrast, saturated fatty acids remain solid at room temperature. All dietary fats consist of a combination of these fatty acids in varying proportions.

Both oils and butter have distinctive roles in the diet, offering unique benefits and often being used interchangeably depending on culinary needs and health considerations. Oils, predominantly composed of unsaturated fatty acids, are frequently lauded for their heart-health benefits, as they can help lower levels of LDL (bad) cholesterol. Additionally, many oils, particularly those derived from seeds and nuts, are rich sources of vitamin E, an antioxidant that protects cells from oxidative stress. Conversely, butter, which is high in saturated fats, has been associated with elevated cholesterol levels and an increased risk of



heart disease when consumed in large quantities. However, butter also provides fat-soluble vitamins such as A, D, E, and K, contributing to its nutritional value.

Once analysed the most relevant nutritional properties of this food group, three single score n-FU (tier 1) have been proposed for impact assessment: (i) energy intake (calories); (ii) the content of MUFA (monounsaturated fatty acid); (iii) the content of vitamin E. Then, a set of oils, seeds oils, and fats from plant as well as some commonly used butters have been selected and relative information collected. The nutritional composition information was obtained from the Ciqual table, one of the most comprehensive food composition databases in Europe [30]. Environmental data, covering the entire lifecycle ‘from cradle to table’, was sourced from the Agribalyse database [31], which provides extensive LCA data for a wide range of agricultural products and food items. Results for each type of fat are presented based on the selected n-FUs and are assessed across two impact categories: contribution to climate change and water use (see Table 1). Within each column, the ranking is indicated using a colour spectrum that ranges from green (lowest impact) to red (highest impact), reflecting the median value.

When using a mass-based n-FU, oils and butter exhibit different environmental impacts with their footprints varying widely depending on the type of product and specific agricultural and processing practices. Generally, butter has a higher carbon footprint due to livestock-related emissions but is relatively low in water intensity. In contrast, while the water footprint of certain oils can be significantly high depending on the crop and region, the carbon footprint of oils is generally lower than that of butter. This underscores a key point: assessing sustainability requires considering multiple impact categories, as a single category alone is not sufficient.

Examining the carbon footprint profile, which measures the contribution to climate change for each nutritional unit, the difference in impact between oils and butters is quite evident. For each n-FU, butters consistently have higher impact indexes, marked in red, indicating significant environmental concerns per nutritional unit. In contrast, oils exhibit more variability in their impact rankings, but generally have lower values.

Energy intake, as an n-FU, shows a ranking closely aligned with that of mass, providing no additional insights since the calorie counts of the products are similar. On the other hand, the other two n-FUs – MUFA and vitamin E – reveal substantial variations in their rankings, offering more nuanced information about environmental impact.

The water footprint profile, which measures the water use required to produce one unit of each nutrient, generally reduces the significance of the impact of butters (i.e., there are fewer red boxes) and highlights the water-intensive nature of certain oils, such as avocado and cottonseed oil. Again, the mass- and energy intake-based n-FUs provide similar perspectives, while MUFA and vitamin E offer a more integrated view of the overall impact.

The overview of each profile provides insights into specific impact categories, but interpreting all selected n-FUs together can be challenging. This is a key limitation of Tier 1 n-FUs, and for this reason integrating nutrient indices as n-FUs should be explored.

4 CONCLUSIONS

The n-LCA approach represents a significant advancement in the field of life cycle assessment, offering a more comprehensive framework for evaluating the sustainability of food systems. While traditional LCA has been invaluable in assessing and documenting the environmental impacts of products and processes, its exclusive focus on ecological factors highlights the need for evolving methodologies that incorporate broader aspects of sustainability, including nutrition and human health. By integrating nutritional



Table 1: Carbon footprint and water footprint profiles of 'oils and fat' food group across a selection of three n-FUs based on single nutrients (tier 1).

	Carbon footprint (kg CO ₂ /FU)				Water footprint (m ³ /FU)			
	1 kg	100 kcal	1 g MUFA	1 mg vit E	1 kg	100 kcal	1 g MUFA	1 mg vit E
Avocado oil	4.88E+00	5.42E-02	7.48E-03	1.08E-02	1.07E+02	1.19E+00	1.64E-01	2.36E-01
Cottonseed oil	2.48E+00	2.76E-02	1.39E-02	7.03E-03	5.22E+01	5.80E-01	2.93E-01	1.48E-01
Frying oil	2.52E+00	2.80E-02	6.38E-03	4.77E-03	1.15E+00	1.28E-02	2.91E-03	2.18E-03
Hazelnut oil	8.18E+00	9.09E-02	1.08E-02	2.86E-02	2.50E+01	2.78E-01	3.32E-02	8.74E-02
Linseed oil	3.54E+00	3.93E-02	1.83E-02	3.94E-02	2.26E+00	2.51E-02	1.17E-02	2.51E-02
Maize/corn oil	3.54E+00	3.93E-02	1.29E-02	2.68E-02	1.05E+01	1.17E-01	3.82E-02	7.95E-02
Olive oil, extra virgin	9.83E-01	1.09E-02	1.34E-03	4.41E-03	2.22E+01	2.47E-01	3.04E-02	9.96E-02
Palm oil	5.55E+00	6.17E-02	1.50E-02	3.49E-02	1.82E+00	2.02E-02	4.92E-03	1.14E-02
Palm oil, refined	6.04E+00	6.71E-02	1.63E-02	3.80E-02	1.89E+00	2.10E-02	5.11E-03	1.19E-02
Peanut oil	4.24E+00	4.71E-02	6.60E-03	2.99E-02	2.45E+01	2.72E-01	3.82E-02	1.73E-01
Rapeseed oil	2.28E+00	2.53E-02	3.82E-03	8.23E-03	6.77E-01	7.52E-03	1.13E-03	2.44E-03
Sesame oil	2.28E+00	2.53E-02	5.67E-03	2.07E-01	6.77E-01	7.52E-03	1.68E-03	6.15E-02
Soy oil	2.84E+00	3.16E-02	1.29E-02	4.66E-02	3.56E-01	3.96E-03	1.61E-03	5.84E-03
Sunflower oil	2.58E+00	2.87E-02	9.35E-03	4.50E-03	1.27E+00	1.41E-02	4.60E-03	2.22E-03
Butter, 39–41% fat, light, unsalted	6.18E+00	1.58E+01	5.78E-02	5.07E-01	1.99E+00	5.09E-02	1.86E-02	1.63E-01
Butter, 60–62% fat, light, lightly salted	7.11E+00	1.28E+01	4.47E-02	4.50E-01	2.29E+00	4.13E-02	1.44E-02	1.45E-01
Butter, 60–62% fat, light, unsalted	7.15E+00	1.30E+01	5.11E-02	5.18E-01	2.30E+00	4.18E-02	1.64E-02	1.67E-01
Butter, 80% fat, lightly salted	7.73E+00	1.05E+01	3.65E-02	3.66E-01	2.48E+00	3.36E-02	1.17E-02	1.18E-01
Butter, 80% fat, salted	7.73E+00	1.06E+01	3.92E-02	4.37E-01	2.48E+00	3.39E-02	1.26E-02	1.40E-01
Butter, 82% fat, unsalted	7.79E+00	1.03E+01	4.04E-02	8.66E-02	2.50E+00	3.32E-02	1.30E-02	2.78E-02
Median value	4.56E+00	5.06E-02	1.34E-02	3.64E-02	2.30E+00	3.37E-02	1.28E-02	8.35E-02

Note: The cells of each column are coloured based on ranking from lowest (green) to highest (red), according to the median value.

considerations, n-LCA moves beyond the conventional scope of LCA, addressing the complex interplay between food production and consumption, and long-term sustainability. This approach shifts the focus toward minimising trade-offs between nourishing populations and safeguarding the environment.

This paper presents a SWOT analysis that reviews the current strengths and weaknesses of the emerging n-LCA approach, underscoring its substantial potential while acknowledging the areas that require further development. One of the most significant challenges is the standardisation of the methodology, particularly in the selection of one or more appropriate n-FUs. Standardisation is crucial to ensuring consistency and comparability across studies, which is vital for the widespread adoption of n-LCA.

By examining a specific food group, this work highlights the benefits of analysing food groups rather than individual food items when assessing and comparing various impacts.

Further research and interdisciplinary collaboration are essential to refine n-LCA techniques and enhance their applicability in diverse contexts. Such efforts will be crucial for developing robust, nuanced tools that can accurately assess the sustainability of food systems, ultimately contributing to more sustainable agricultural practices and improved public health outcomes.

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REFERENCES

- [1] Shukla, P.R. et al. (eds.), *Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. IPCC, 2019. <https://www.ipcc.ch/site/assets/uploads/2019/11/SRCCL-Full-Report-Compiled-191128.pdf>. Accessed on: Jun. 2024.
- [2] Battle-Bayer, L., Aldac, R., Bala A. & Fullana-i-Palmer, P., Toward sustainable dietary patterns under a water–energy–food nexus life cycle thinking approach. *Current Opinion in Environmental Science and Health*, **13**, pp. 61–67, 2020.
- [3] Wiebe, K. et al., Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios. *Environmental Research Letters*, **10**(8), 085010, 2015.
- [4] Poore, J. & Nemecek, T., Reducing food's environmental impacts through producers and consumers. *Science*, **360**, pp. 987–992, 2018.
- [5] Audsley, A. et al., Harmonisation of environmental life cycle assessment for agriculture. Final Report of Concerted Action AIR3-CT94-2028, Silsoe Research Institute, Bedford, UK, 1997.
- [6] Cucurachi, S., Scherer, L., Guinée, J. & Tukker, A., Life cycle assessment of food systems. *One Earth*, **1**(3), pp. 292–297, 2019.
- [7] Notarnicola, B., Sala, S., Anton, A., McLaren, S., Saouter, E. & Sonesson U., The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges. *Journal of Cleaner Production*, **140**(2), pp. 399–409, 2017.



- [8] Notarnicola, B. (ed.), 7th International conference on life cycle assessment in the agri-food sector (LCA Food 2010), 22–24 September 2010, Bari (Italy). *International Journal of Life Cycle Assessment*, **16**(2), pp. 102–105, 2011.
- [9] Clune, S., Crossin, E. & Vergheze, K., Systematic review of greenhouse gas emissions for different fresh food categories. *Journal of Cleaner Production*, **140**, pp. 766–783, 2017.
- [10] Niccolucci, V., Marchi, M., Neri, E., Pulselli, R.M., Bastianoni, S. & Marchettini, N., Insights into nitrogen footprint accounting for products and application to an organic pig farm. *Ecological Indicators*, **133**, 108411, 2021.
- [11] European Commission, Joint Research Centre & Institute for Environment and Sustainability, *International Reference Life Cycle Data System (ILCD) Handbook: General guide for Life Cycle Assessment – Detailed Guidance*. EUR 24708 EN. Publications Office of the European Union: Luxembourg, 2010.
- [12] Stylianou, K.S., Heller, M.C., Fulgoni, V.L., Ernstoff, A.S., Keoleian, G.A. & Jolliet, O., A life cycle assessment framework combining nutritional and environmental health impacts of diet: A case study on milk. *International Journal of Life Cycle Assessment*, **21**(5), pp. 734–746, 2016.
- [13] Grigoriadis, V., Nugent, A. & Brereton, P., Working towards a combined measure for describing environmental impact and nutritive value of foods: A review. *Trends in Food Science and Technology*, **112**, pp. 298–311, 2021.
- [14] Green, A., Nemecek, T., Chaudhary, A. & Mathys, A., Assessing nutritional, health, and environmental sustainability dimensions of agri-food production. *Global Food Security*, **26**, 100406, 2020.
- [15] Green, A., Nemecek, T., Smetana, S. & Mathys, A., Reconciling regionally-explicit nutritional needs with environmental protection by means of nutritional life cycle assessment. *Journal of Cleaner Production*, **312**, 127696, 2021.
- [16] Hallström, E., Davis, J., Woodhouse, A. & Sonesson, U., Using dietary quality scores to assess sustainability of food products and human diets: A systematic review. *Ecological Indicators*, **93**, pp. 219–230, 2018.
- [17] Saarinen, M., Fogelholm, M., Tahvonen, R. & Kurppa, S., Taking nutrition into account within the life cycle assessment of food products. *Journal of Cleaner Production*, **149**, pp. 828–844, 2017.
- [18] Weidema, B.P. & Stylianou, K.S., Nutrition in the life cycle assessment of foods: Function or impact? *International Journal of Life Cycle Assessment*, **25**, pp. 1210–1216, 2020.
- [19] Kyttä, V. et al., Product-group-specific nutrient index as a nutritional functional unit for the life cycle assessment of protein-rich foods. *International Journal of Life Cycle Assessment*, **28**, pp. 1672–1688, 2023.
- [20] McLaren, S. et al., Integration of environment and nutrition in life cycle assessment of food items: Opportunities and challenges. FAO: Rome, 2021.
<https://openknowledge.fao.org/server/api/core/bitstreams/b881d890-f90b-435e-8af2-24b19e342a11/content>. Accessed on: Jun. 2024.
- [21] McAuliffe, G.A. et al., A commentary on key methodological developments related to nutritional life cycle assessment (nLCA) generated throughout a 6-year strategic scientific programme. *Food and Energy Security*, **12**, e480, 2023.
- [22] Ridoutt, B.G., Bringing nutrition and life cycle assessment together (nutritional LCA): Opportunities and risks. *International Journal of Life Cycle Assessment*, **26**(7), pp. 1932–1936, 2021.



- [23] Nemecek, T., Jungbluth, N., Mila i Canals, L.M. & Schenck, R., Environmental impacts of food consumption and nutrition: Where are we and what is next? *International Journal of Life Cycle Assessment*, **21**, pp. 607–620, 2016.
- [24] McAuliffe, G.A., Takahashi, T. & Lee, M.R.F., Applications of nutritional functional units in commodity-level life cycle assessment (LCA) of agri-food systems. *International Journal of Life Cycle Assessment*, **25**, pp. 208–221, 2020.
- [25] Masset, G., Vieux, F. & Darmon, N., Which functional unit to identify sustainable foods? *Public Health Nutrition*, **18**(13), pp. 2488–2497, 2015.
- [26] Stylianou, K.S., Nutritional and environmental impacts of foods on human health, environmental health sciences. PhD thesis, University of Michigan, Ann Arbor, Michigan, USA, 2018. <https://deepblue.lib.umich.edu/handle/2027.42/147641>. Accessed on: Jun. 2024.
- [27] ISO, ISO 14044:2006/AMD 1:2017. Environmental management: Life cycle assessment – Requirements and guidelines – Amendment 1.
- [28] Food SCP RT, 2013. ENVIFOOD Protocol, Environmental Assessment of Food and Drink *Protocol*. European Food Sustainable Consumption and Production Round Table (SCP RT). Working Group 1. Brussels, Belgium.
- [29] Fulgoni, V.L., Keast, D.R. & Drewnowski, A., Development and validation of the nutrient-rich foods index: A tool to measure nutritional quality of foods. *Journal of Nutrition*, **139**, pp. 1549–1554, 2009.
- [30] Anses, The 2020 ANSES-CIQUAL table. <https://ciqual.anses.fr/#/cms/2020-anses-ciqual-table/node/19>. Accessed on: Jun. 2024.
- [31] Agribalyse, Agribalyse database version 3.1.1. <https://agribalyse.ademe.fr/app/aliments/>. Accessed on: Jun. 2024.

