ISSN 2300-5599

ACTA INNOVATIONS

CENTRUM
BADAŃ I INNOWACJI
PRO - AKADEMIA
RESEARCH AND INNOVATION CENTRE

no. 36

September 2020

Acta Innovations

quarterly

no. 36

Konstantynów Łódzki, Poland, September 2020

ISSN 2300-5599

Original version: online journal

Online open access: www.proakademia.eu/en/acta-innovations

Articles published in this journal are peer-reviewed

Publisher:

Research and Innovation Centre Pro-Akademia
9/11 Innowacyjna Street
95-050 Konstantynów Łódzki
Poland

Editor in Chief:
Rafał Marcin Łukasik, Ph.D.

The tasks: "Purchase of digital IDs for digital documents", "Purchase or creation of anti plagramis or purchase of licenses of those programmes", "Editors training", "Verification and correction of scientific articles in journal, including correction of translation in to foreign languages articles and abstracts", "Raising of the quality of review", "Dissemination of information regarding the journal" are financed under the Agreement no. 39/WCN/2019/1 from the resources of the Ministry of Science and Higher Education, constituting assistance designated under the programme "Support for scientific journals".

Zadania: „Zakup cyfrowych identyfikatorów dokumentów elektronicznych", „Zakup albo wytworzenie programów antyplagiatowych albo zakup licencji na te programy", „Szkolenia redaktorów", „Weryfikacja i korekta *artykułów naukowych w czasopiśmie, w tym korekta tłumaczenia na języki obce tych artykułów i ich streszczeń", „Podniesienie poziomu merytorycznego recenzji", „Upowszechnianie informacji o czasopiśmie" są finansowane w ramach umowy 39/WCN/2019/1 ze środków Ministra Nauki i Szkolnictwa Wyższego stanowiących pomoc przyznaną w ramach programu „Wsparcie dla czasopism naukowych".*

Ministerstwo Nauki
i Szkolnictwa Wyższego

ACTA INNOVATIONS

no. 36

September 2020

Contents

"The Stone Age did not end because humans ran out of stones.
It ended because it was time for a re-think about how we live."
William McDonough

A PARADIGM SHIFT IN SUSTAINABILITY: FROM LINES TO CIRCLES

Piergiuseppe Morone
Bioeconomy in Transition Research Group – Unitelma Sapienza University of Rome
Uffici di Viale Regina Elena 291, 00161 Roma, Italy, piergiuseppe.morone@unitelmasapienza.it
https://orcid.org/0000-0002-3240-7089

Gülşah Yilan
Marmara University, Department of Chemical Engineering
Göztepe Kampüsü, 34722, İstanbul, Turkey
https://orcid.org/0000-0002-6392-8469

Abstract
The concept of sustainability is attracting great attention as societies become increasingly aware of the environmental consequences of their actions. One of the most critical challenges that humankind is facing is the scarcity of resources, which are expected to reach their limits in the foreseeable future. Associated with this, there is increasing waste generated as a consequence of rapid growth in the world population (particularly in urban areas) and a parallel rise in global income. To cope with these problems, a linear strategy has been applied to increase efficiency by reducing the use of materials and energy in order to lessen environmental impacts. However, this cradle to grave approach has proven inadequate, due to a lack of attention to several economic and social aspects. A paradigm shift is thus required to re-think and innovate processes (as early as in the design phase) in such a way that materials and energy are used more effectively within a closed-loop system. This strategy, known as the cradle-to-cradle approach, relies on the assumption that everything is a resource for something else since no waste is ever generated in nature. In line with the cradle-to-cradle approach, the bio-inspired circular economy concept aims at eco-effectiveness, rather than eco-efficiency. While the circular economy has neither a confirmed definition nor a standardized methodology, it nonetheless carries significant importance, since it "is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles," in accordance with the goals of the 2030 Agenda for Sustainable Development. Despite some controversial opinions that "circles are not spirals, and for growth to occur, spirals with ever-increasing radii are required," the circular economy concept is taking a central role in the sustainable development debate and, for this reason, deserves attention. The aim of this paper is to shed light on this debate, pointing out the main features of the emerging circular paradigm along with sustainability transition theories and circularity evaluation tools.

Keywords
circular economy; circularity metrics; sustainability transition; paradigm shift.

Introduction
Humankind is facing difficult challenges associated with our increasingly unsustainable lifestyles (involving, e.g., mass consumption, aggressive industrialization, and increased energy demand and urban waste generation), aggravated by an ongoing exponential increase in the global population. In response to these threats, societies are becoming ever more aware of the consequences of their actions on ecosystems. Thus, there is ongoing search for sustainable ways of producing goods used in everyday life and also in modern technological applications. In the search for cleaner technologies, raw materials are of crucial importance. Especially, critical raw materials (i.e. materials that have high economic value coupled with a high risk of supply) draw great attention since they are linked to all industries across all supply chain stages [1]. In addition to the scarcity issues, the low recycling rate of these materials results in the loss of significant economic opportunities that, in turn, pushes practitioners to develop holistic approaches to evaluate elemental sustainability [2,3]. Due to the scarcity of raw materials along with the related economic and environmental impacts, a sustainability debate has flourished among

https://doi.org/10.32933/ActaInnovations.36.1• ISSN 2300-5599 •

academics, analysts, and policymakers. A commonly proposed solution for the problems associated with unsustainable human behaviour is the triple bottom line (TBL) strategy, which aims at evaluating economic performance alongside social and environmental impacts. However, TBL strategies do not seek to balance economic, environmental, and social aims; rather, they – predictably – hold economic objectives as paramount. Thus, a different perspective is required to assess sustainability. A potentially useful strategy could be obtained by translating TBL strategies to their triple top line (TTL) counterparts, which aim at enhancing the well-being of nature and culture while generating economic value. TTL strategies enable companies to assess the environmental and social impacts of their activities while minimizing their ecological footprint [4].

In the TTL approach, linear *cradle to grave* strategies are replaced with circular *cradle-to-cradle* strategies. Traditionally, cradle to grave systems focus on reducing energy and material demand, and thus decreasing the environmental footprint by increasing eco-efficiency; this strategy is also known as the *take-make-waste* approach. On the other hand, the cradle-to-cradle approach shifts the paradigm by re-thinking the processes in terms of material and energy, implementing innovations as early as in the design phase to create a closed-loop system for eco-effectiveness [5,6]. This strategy suggests that everything is a resource for something else, given the principle that no waste is ever generated in nature. The cradle-to-cradle approach is an idealized pattern for sustainability that requires support from driving tools such as the circular economy (CE). Therefore, the focus of this paper is on the bio-inspired circular economy concept, which aims – much like the cradle-to-cradle approach – at achieving eco-effectiveness, rather than eco-efficiency.

As the CE is the manifestation of a paradigm shift, it implies significant changes in societal legislation, production, and consumption, taking nature as an inspiration for responding to social and environmental needs. CE systems maintain the added-value of products by innovating for as long as possible and eliminating waste. This requires full systemic change, involving innovation in not only technologies but also organizations, society, finance, and policies [6].

The CE is key to achieving the Sustainable Development Goals of the 2030 Agenda, which rely on a new paradigm integrating techniques, tools, and frameworks under principles of circularity, eco-effectiveness, and harmlessness [7]. The CE is expected to promote economic growth by creating new businesses and job opportunities, reducing material costs, dampening price volatility, and improving supply security, while simultaneously reducing environmental pressures and impacts [8,9].

Literature on the CE is increasing rapidly, covering both its conceptualization and its implementation. Korhonen et al. made a significant contribution to CE studies with their critical analysis of the role of the CE in sustainable development [10]. The study evaluated the CE concept, as well as its limitations, in terms of environmental sustainability. Pesce et al. identified the basic drivers and barriers to implementing CE principles at the corporate micro level and the organization of CE principles [11]. Beyond these examples, many other studies have considered specific CE cases [12-14].

Some authors have predicted the timing of the sixth Kondratieff cycle, suggesting that it will be driven by resource efficiency and clean technology – indicating sustainability [15]. However, a transition to a more sustainable regime implies more than simply a shift from one technological configuration to another, but "a change of the underlying structure which regulates technical change" [16]. A regime shift arises through changes to the regulative (i.e. formal rules, laws, etc.), normative (i.e. values, norms, etc.) and cognitive (i.e. priorities, problem agendas, beliefs, etc.) rules guiding behaviour in practice [17]. Such changes may affect changes within a particular value chain (i.e. vertical change) or in each part of a particular value chain (i.e. horizontal change). In fact, they might even change the entire configuration of an established value chain [18].

As the linear nature of cradle to grave life cycle assessment (LCA) strategies has urged practitioners to adopt circular cradle-to-cradle approaches, and as the number of evaluation tools has increased, the need for a standardized methodology to measure circularity has arisen. Although some standards for implementing CE principles exist (e.g. the British Standard BS 8001:2017 [19], CEN and CENELEC Standards EN45558 [20] and EN45559 [21]), none has achieved consensus among practitioners. The latest development to establish a common basis was the action plan published by the European Commission on March 11, 2020 [22]. This plan

https://doi.org/10.32933/ActaInnovations.36.1• ISSN 2300-5599 •

proposed a roadmap for making the EU economy sustainable via "turning climate and environmental challenges into opportunities across all policy areas and making the transition just and inclusive for all." Moreover, some organizations and private companies have tried to establish their own circularity measurement tools (e.g. the Material Circularity Indicators [23] and Circulytics [24] proposed by the Ellen MacArthur Foundation; the CirculAbility Model [25] proposed by Enel); these tools may offer practical potential, and they are examined in detail in a later section of this paper.

Before entering into a deep methodological discussion, it should be mentioned that some objections to the CE concept have been raised. For example, in his controversial paper, Skene questioned the biological basis claimed for the principles underpinning the CE (i.e. thermodynamic and ecological principles) and argued that the natural world operates in a very different way from that portrayed in the CE literature [26]. Skene concluded that the CE is unfit to deliver both sustainability and growth. Specifically, he held that the CE works against both the laws of thermodynamics and the underpinning principles of nature; hence, it can hardly be considered sustainable. Moreover, circles do not lead to growth, as this requires ever-increasing spirals. Despite this controversial position, the CE has taken a central role in the debate over sustainable development and the sustainability transition, and, in this respect, its definition and measurement deserve attention.

This paper has the following structure: Section 2 provides a literature review to introduce the CE concept; Section 3 explains transition theories with respect to the move from a linear to a circular model; Section 4 introduces the tools used for measuring circularity; Section 5 mentions the impacts of CE on sustainability dimensions and, finally, Section 6 provides concluding remarks and recommendations.

Literature review: Introducing the cradle to cradle CE concept

Until recently, sustainability assessment strategies used the linear approach of measuring cradle to grave material flows in order to model typical take-make-waste behaviours. This strategy aimed at minimizing material and energy consumption and thereby reducing the environmental footprint in an attempt to increase efficiency. However, as the sustainability concept has widened its perspective to include economic and social aspects, the need for a fundamental conceptual shift has emerged, supporting a cradle-to-cradle system. Cradle to cradle systems are powered by renewable energy, whereby materials flow in safe, regenerative, closed-loop cycles [5,6]. Through this perspective, processes must be re-thought and innovated (as early as in the design phase) to ensure that benign, valuable, high-tech synthetics, mineral resources, and energy are used effectively in cycles of production, use, recovery and remanufacture.

The cradle-to-cradle approach is an eco-effective strategy that holds that everything can be converted into valuable nutrients (value-added products) at the end of its life. The approach involves the design of "commercially productive, socially beneficial, and ecologically intelligent" processes [2]. One eco-effective strategy is known as *stock optimization,* which is based on the recognition of the limited nature of Earth's resources and the need to maximizing their value. As summarized by Kalymkova et al., the stock optimization concept is directly linked to various economic theories such as spaceman economy, steady-state economy, industrial ecology, and cradle-to-cradle [27]. In particular, the cradle-to-cradle perspective has significant potential to create a new paradigm for industry, whereby human activity can generate a wide spectrum of ecological, social, and economic value.

Similar to the cradle-to-cradle concept, some bio-inspired concepts (e.g. CE, green economy and bioeconomy) aim at eco-effectiveness, rather than eco-efficiency. Although these concepts are often used interchangeably, there are slight differences between them that should not be overlooked [28]. Geisendorf and Pietrulla conducted a comparative assessment of CE concepts, concluding that – even though they do not indicate precisely the same thing – the cradle-to-cradle approach is the most aligned with the CE perspective [29].

The CE concept is mainly based on the idea that products or processes should be designed to turn materials into nutrients via two distinct metabolisms defined by the creators of the cradle-to-cradle concept [6]. The biological metabolism (or cycle) considers products with the potential to be consumed (i.e. *products of consumption*). At the end of their lives, products of consumption may serve as nutrients for living systems and return to the natural environment to feed biological processes. The second metabolism – the technical metabolism (or cycle) – considers durable goods that provide a service to customers (i.e. *products of service*). Products of service can remain safely in a closed-loop system of manufacture, recovery, and reuse, maintaining their highest value through many product life cycles. As a result, circular economy systems keep the added-value in products for as long as possible and eliminate waste.

Owing to its high potential, the CE approach has gathered great interest from a variety of disciplines, including economics, chemistry, engineering, and architecture – despite the lack of an agreed-upon definition and a standardized implementation methodology. In their comprehensive review, Prieto-Sandoval et al. provided one of the most extensive definitions of the CE as "an economic system that represents a change of paradigm in the way that human society is interrelated with nature and aims to prevent the depletion of resources, close energy and materials loops, and facilitate sustainable development through its implementation at the micro (enterprises and consumers), meso (economic agents integrated into symbiosis) and macro (city, regions, and governments) levels [30]." The idea of paradigm shift relates closely to transition theory and, more specifically, to the growing debate over the transition to sustainability.

Transitioning from a linear to a circular model

For many years, environmental impact assessment studies – based on the implementation of technological innovations – were considered sufficient to evaluate sustainability. To set a global standard for sustainable development, the United Nations proposed 17 Sustainable Development Goals (SDGs) in their 2030 Agenda [7]. As a result of their conceptual analysis of each SDG, along with five case studies set across the world, Leal Filho et al. noted that all of the SDGs are strongly interlinked in terms of their ability to tackle environmental sustainability challenges [31].

Nonetheless, even if a product's environmental performance (i.e. eco-efficiency) is improved, this may not always generate greater environmental sustainability [32–35]. By the same token, a greater circularity of products or production systems does not always correspond to greater social inclusion (e.g. human rights, gender equality, fair trade, etc.). The solution is therefore to identify the best compromise. A *global* list of environmental and/or social priorities should be drawn up and the response strategy built around it. In his pioneering study, Geels performed an analysis stemming from the sociology of technology, building upon the fact that "technology, of itself, has no power, does nothing. Only in association with human agency, social structures, and organizations does technology fulfil functions [36]." Following this line of reasoning, a comprehensive sustainability assessment approach would require the evaluation of all societal and economic practices, values, and attitudes that result from or lead to technological, social, ecological, and political innovations [37–40]. Accordingly, a growing number of studies have examined the sustainability transitions of socio-technical systems, especially in the areas of sustainable policymaking and planning activities for a low-carbon future [41–44].

Before discussing transition theories, it is worth defining socio-technical systems as "a configuration of products, processes, services, and infrastructures, regulations, skills, preferences, expectations, and actors (e.g., producers, suppliers, policymakers, users) that fulfil societal needs such as energy, food, or mobility provision" [41]. Theories of the transition to sustainability are predominantly based on the ways in which system innovations (i.e. transitions from an incumbent socio-technical system to a new and more sustainable system) occur and how transition interventions can be organized [46].

Although the literature on sustainability transition theories is increasing[2], this paper focuses on the multi-level perspective (MLP) developed by Rip and Kemp [47], Geels [36], Geels and Schot [48] and Grin [49]. The MLP is one of the most significant analytical frameworks in the field, owing to its flexibility and usefulness in identifying transition patterns and factors contributing to inertia in existing systems [17]. In the remainder of this section, the conceptual basis of the MLP is explained; following this, some controversial opinions about its application are introduced.

Originally, the MLP was constructed as a multi-dimensional approach fostering ideas from evolutionary economics, the sociology of innovation, and neo-institutional theory to understand technological transitions (i.e. "technological changes in the way societal functions are fulfilled") [36]. Later, it was improved to serve as a heuristic device for sustainability transition studies [50-52].

[2] See, for instance, Bergek et al. [87], Hekkert et al. [88] and Jacobsson and Bergek [89] for the basics of the methodology; and Hacking et al. [90], van Welie et al. [91], Sawulski et al. [92], el Bilali [93] and Kushnir et al. [94] for recent case studies.

https://doi.org/10.32933/ActaInnovations.36.1• ISSN 2300-5599 •

According to the MLP, a socio-technical transition emerges from the interplay between processes at the three levels of a nested hierarchy: (i) niche innovations, (ii) socio-technical regimes, and (iii) the exogenous socio-technical landscape [36]. Niche innovations occur at the micro-level, where path-breaking transitions tend to develop and receive nourishment; the niches function as protective spaces that shield innovations from mainstream selection pressures. Socio-technical regimes represent the meso level unit and refer to the semi-coherent set of rules pertaining to different social groups; the socio-technical landscape refers to wider technology-*external* factors.

Existing regimes are pressured by niche innovations and landscape developments, which open so-called *windows of opportunity* for transitions, in general, and sustainability transitions, in particular [53]. However, socio-technical transitions do not occur overnight; rather, they progress through four developmental stages, which may take several decades to complete [54]. The first phase is characterized by *experimentation* and trial-and-error learning, with radical niche innovations that gradually build up internal momentum. In the second phase, innovations *stabilize* in one or more market niches, providing a more reliable flow of resources and placing pressure on the system and regime. In the third phase, the radical innovations *diffuse* into mainstream markets. Finally, in the fourth phase, the new socio-technical system disrupts the existing system (fully or in part) and becomes *institutionalized* and anchored.

The MLP perspective forms a bridge between evolutionary economics and technology studies. Its strength is simultaneously its weakness. It is a fairly complex perspective, requiring much data – often of a qualitative nature [36]. Nevertheless, there are some controversial debates about the ontological and epistemological perspectives via critical realism [17,41]. Critics claim that an understanding of why certain developments happen requires examination of the relational interplay between the multiple structural factors relevant to the specific conjuncture. To understand whether a sustainability transition will occur or not, it is vital to assess both landscape pressure and niche readiness, as the first destabilizes the incumbent regime and the second provides a viable alternative [15]. However, the MLP approach does not provide an exact solution to such problems.

Another important critique states that transition studies do not necessarily indicate sustainability outcomes or impacts. Assuming that "green" innovations are intrinsically positive, their degree of sustainability improvement is not determined. Geels accepts that the outcomes of impact assessments are often determined by the interpretations of life-cycle analysts or modellers [54]. In the authors' view, this affirmation clearly states that the implementation of transition theories must be supported by complementary evaluation tools. This need becomes all the more relevant when considering complex transitions such as the transition from a linear to a circular model. In this case, multiple technologies are simultaneously involved, in both complementary and substitute ways. At the same time, behavioural changes are required for the transition to be effective. In order to assess what is truly circular and sustainable (in terms of both production and consumption), specific tools and metrics are needed to reduce the risk of greenwashing or – worse – a transition to unsustainability. A brief history of circularity measurement studies and a closer look at some of the recently developed tools for measuring circularity are presented in the following section.

<u>Tools for measuring the CE</u>

LCA is classified as a unique environmental management framework for sustainable decision-making [55]. As the popularity of the LCA methodology has increased, its potential as a tool to assess circularity has become a matter of debate among practitioners. In their recent publication, Corona et al. provided a comprehensive review of the most used frameworks to assess the circularity of products and services [56]. They indicated that the LCA was the most used framework amongst the seven measurement indices, nine assessment indicators, and three assessment frameworks they considered, and concluded that the LCA is a potentially useful tool for measuring circularity. Furthermore, Lokesh et al. reported an interesting example of how the LCA can serve as a hybridized sustainability metric of circularity [57]. They combined resource efficiency indicators from LCA applications with green chemistry metrics and principles to bridge gaps for both bio-based and fossil-based products.
Despite its great potential, the LCA has limitations that directly affect the quality of its assessment. In particular,

LCA results are difficult to map onto social and economic impacts, as Reap indicated in an extensive two-part review [58,59]. Although Bjørn et al. suggested that LCA indicators could be improved by translating midpoint indicator scores to absolute environmental sustainability indicators, taking *carrying capacity* as a reference, sustainability assessment studies still require a more comprehensive perspective [32].

https://doi.org/10.32933/ActaInnovations.36.1• ISSN 2300-5599 •

In addition to enhancing the potential applications of LCA, researchers have also aimed at supporting it with other tools to broaden its perspective to include economic and social (in addition to environmental) aspects of sustainability [60,61]. This challenge has been taken up by a growing number of scholars, analysts, and policymakers, who have proposed decision-making tools such as multi-criteria decision analysis (MCDA) and cost-benefit analysis (CBA) [62–68]. Furthermore, a number of sustainability assessment studies have applied multi-pillar analysis, evaluating economic and social aspects as well as environmental factors [69–72].

Several researchers have combined different sustainability evaluation tools to affect a broader perspective, in line with the concept of circularity. For example, Niero and Kalbar proposed the combination of different circularity and LCA-based indicators to measure CE performance at macro, meso, and micro levels, via MCDA [73]. This indicated a novel approach to assessing circularity at a product level, drawing on CE and eco-efficiency perspectives. Thus, the study provided a significant contribution to the literature, in terms of both its evaluation of suitable metrics and its proposed framework for assessing product circularity.

Numerous evaluation tools and metrics have been reported in the literature. In particular, Elia et al. compared index-based methodologies in macro, meso, and micro levels to assess the capacity of certain environmental assessment tools to satisfy CE requirements [74]. Mesa et al. referenced sustainability measurement in the product development process and existing indicators for the CE [75]. Finally, in their extensive study, Parchomenko et al. identified and assessed 63 circular economy metrics and approaches [76]. Overall, these three papers (appeared on the *Journal of Cleaner Production* over the period 2017-2019) provide a rather comprehensive overview of the theoretical and empirical debate around indicators and tools developed to assess sustainability at various levels (both geographical and technological) with different aspects of the CE.

In light of the increasing number of evaluation tools, the need for a standardized methodology to measure circularity has become evident. The BS 8001:2017 was the world's first CE standard, developed to "help organizations and individuals consider and implement more circular and sustainable practices within their businesses, whether through improved ways of working, providing more circular products and services or redesigning their entire business model and value proposition" [19]. Following this, the European Commission introduced the first of two CE design protocols (EN45558 and EN45559), constituting a framework for standards for "material efficiency that would establish future ecodesign requirements on, amongst others, durability, reparability, and recyclability of products" [20,21]. The most recent development by the European Commission was the action plan introduced on March 11, 2020. This plan proposed a roadmap for making the EU economy sustainable, with the aim of "turning climate and environmental challenges into opportunities across all policy areas and making the transition just and inclusive for all [22]." The framework is expected to boost the efficient use of resources by promoting clean CE, restoring biodiversity, and reducing pollution. While the number of metrics introduced in the literature has steadily increased, no consensus has been reached among practitioners as to which metric is superior. In the remainder of this section, three evaluation tools that the authors hold to offer practical potential are examined in further detail.

The Circularity Indicators Project, proposed by the Ellen MacArthur Foundation in collaboration with Granta Design and financially supported by the EU, represented the first attempt to standardize the methodology [23]. The goal of the project was to develop a measurement system to assess the circularity of products and companies, using the material circularity indicator (MCI). The MCI shares some commonalities with LCA methodologies, such that most of the inventory data required for the LCA are also required for the MCI, and the complementary impact indicators may be derived from an LCA approach. Nonetheless, the difference between these methodologies rests on their scope: the LCA considers the entire product life cycle, whereas the MCI focuses on the material flow in the use phase, only. The MCI had a pioneering role as the first model to assess circularity at both a product and a company level (the company level MCI is calculated as a weighted average of all product level MCIs). However, it focuses exclusively on technical cycles and materials from non-renewable sources, providing very limited insight into consumption products. Thus, a better understanding is required to assess all dimensions of circularity.

The Italian multinational energy company Enel recently developed a tool to assess circularity, known as the *CirculAbility* model [25]. This model is based on a set of key performance indicators (KPIs) used to measure, compare, and improve circularity in the context of the CE. The goal is to combine a number of KPIs to define a single circularity index covering all circularity parameters of the studied product or project. The tool can be used to measure circularity at a company and/or product level. The model covers all pillars of the CE, via two indicators: flow circularity and usage circularity. Flow circularity considers sustainable inputs and end-of-life activities for materials and energy. Usage circularity, in contrast, pertains to life extension, sharing, and products as service activities. The report published by Enel explains the empirical basis of the application procedure; however, it does not provide adequate detail on the limitations of the model. The documentation should be improved to give practitioners a clearer idea of how to use CirculAbility to evaluate circularity.

To achieve a comprehensive analysis, the material circularity indicator methodology may be enhanced by the introduction of consumption products. To this end, a new tool, *Circulytics*, was recently proposed by the Ellen MacArthur Foundation, in collaboration with various global partners and CE100 member organizations [24]. The tool is useful for measuring both product and company circularity scores. To produce an overall circularity score (i.e. a Circulytics score), a three-step weighting methodology is applied, starting with sustainability indicators. First, a number of indicators (specific to the studied case) are selected and used to calculate a weighted average for each of seven key themes: (i) strategy and planning; (ii) people and skills; (iii) systems, processes and infrastructure; (iv) innovation; (v) external engagement; (vi) inputs; and (vii) outputs. Similarly, the second step calculates another weighted average for two category-level scores: enablers and outcomes. Finally, the third step produces a single representative Circulytics score. Although the methodology has some limitations (such as a limited number of indicators to model the entire mechanism and uncertainties related to the normalization and weighting methods applied), it holds significant potential to assist companies in their transition to the CE. Moreover, the tool has the advantage of acting as an industrial benchmark over the long term, as an increasing number of companies from different industries are adopting the proposed methodology to measure their circularity.

The Impacts of CE on Different Sustainability Issues

The CE approach aims at achieving a continuous, fair, and effective economic system, guaranteed through the sustainable use of finite resources; in other words, it recognises both the presence of ecological limits and ecosystem constraints and the need of reducing waste and emissions due to human activities [77-79]. It is also stated in the EMF report that the CE functions as a value-creation mechanism to "(i) preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows; (ii) optimize resource yields by circulating products, components, and materials at the highest utility at all times in both technical and biological cycles; and (iii) foster system effectiveness by revealing and designing out negative externalities" [80]. In this respect, the CE has significant impacts on various dimensions of the economic system, offering promising solutions to the problems associated with linear production and consumption behaviours.

Since the CE is an umbrella concept, it is not always possible to draw clear lines between different dimensions of sustainability in the application of CE principles. For example, both economic and environmental impacts are simultaneously improved when resources are used efficiently and the environmental impacts - associated with material extraction and processing, product manufacture, use, and end-of-life activities - decrease. Thus, the CE offers a strategy to decouple resource use and environmental impact from economic growth – even though no conclusive evidence is proposed so far about how the CE fulfils this mission [77]. Some other authors also argue that the CE concept represents a 'welcome novelty' because it demonstrates that the linear economy is not sustainable and, at the same time, a 'worrisome novelty' because it does not seriously engage with a comprehensive understanding of the biophysical roots of the economic process [81].

However, there is a consensus on the idea that "the transition to a more circular economy requires changes throughout value chains, from product design to new business and market models, from new ways of turning waste into a resource to new modes of consumer behaviour. This implies full systemic change and innovation not only in technologies but also in organization, society, finance methods, and policies" [82]. As influential actors of the value chain, retailers have a special role in linking producers/suppliers and consumers. On the one hand, they exert pressure on their suppliers to shift to more sustainable business models while also encouraging changes in consumer behaviour, so as to make positive contributions to the environment and society as a whole [83,84]. Large retailers such as Tesco, Walmart, and Carrefour are increasingly presenting themselves as sustainability drivers that care for the environment, support local communities, provide healthy options to customers, purchase and sell products responsibly, and create jobs; i.e. they promote a CE model in an overall sense. Several studies mention that market driving companies (e.g. IKEA, Southwest Airlines, and Starbucks, Swatch, Amazon.com, Dell, FedEx, H&M) create a positive public perception and dominate the sector they belong to, by integrating CE principles into their agendas [83,85].

Conclusions

This paper addresses the transition from a linear to a circular model, required to meet global challenges pertaining to sustainability. Specifically, it argues that the linear strategy, that has long been applied to increase efficiency by reducing the use of materials and energy in a cradle to grave fashion, has proven inadequate to effectively tackle sustainability problems, due to a lack of attention to economic and social aspects. A paradigm shift is therefore required to ensure that materials and energy are used more efficiently through innovations (implemented as early as possible in the design phase) to create a closed-loop system. Thus, the cradle to grave approach must be replaced by a holistic cradle-to-cradle approach, which is an idealized pattern for sustainability requiring support from driving tools such as the CE.

The transition to sustainability “must be a qualitative shift, where the new system has qualitatively different emergent properties” [17]. For this to occur, in line with the MLP, combined pressure from the macro-level (i.e. the landscape on which the vision for a new resource-efficient system is shaped and nurtured) and the micro-level (i.e. the niches in which innovations are developed and allowed to mature in a protected space) must be exerted on the incumbent regime (i.e. the dominant linear model of production).

However, not all changes may point in the right direction, and the current lack of metrics to measure circularity may pose a serious hurdle to effective deployment of the new circular economic model. To address this challenge, existing indicators were reviewed and their limitations were noted. The authors hope this work will provide solid ground for the further development of metrics and indicators and pave the way to a truly sustainable transition towards a CE.

This shift from linearity to circularity is all more relevant having in mind the COVID-19 crisis, as it holds a significant number of economically attractive answers to the current situation. For example, the fragility of many global supply chains, seen in response to the need for medical equipment, opened the debate on the need for stock availability and short supply chains to increase systemic resilience. Another important domain is the highly sensitive area of centralized food production and the related long-distance transport via supply chains. Some cities faced problems with food supply during lockdowns and the need for shorter producer-to-consumer models emerged. Some specific measures have already been taken about mobility and transport, i.e. giving more space to pedestrians and cyclists and also limiting the speed of motor vehicles across the city. Therefore, the CE solutions can find the chance to become the mainstream in such a dynamic environment, combining economic regeneration, better societal outcomes, and climate targets [86].

Conflict of interest

There are no conflicts to declare.

Acknowledgments

This research has not been supported by any external funding.

References

[1] European Commission (2010) Critical Raw Materials for the EU. Report of the Ad-hoc Working Group on Defining Critical Raw Materials. European Commission, Enterprise and Industry. Available at https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en [accessed May 31, 2020].

[2] McElroy CR, Constantinou A, Jones LC, Summerton L, Clark JH. Towards a holistic approach to metrics for the 21st century pharmaceutical industry. Green Chemistry 17 (2015), 3111-3121.

[3] Massari S, Ruberti M. Rare earth elements as critical raw materials: Focus on international markets and future strategies. Resources Policy 38 (2013), 36–43.

[4] Mcdonough W, Braungart M. Design for the triple top line: New tools for sustainable commerce. Corporate Environmental Strategy 9 (2002), 251–258.

[5] McDonough W, Braungart M, Anastas PT, Zimmerman JB. Applying the principles of green engineering to cradle-to-cradle design. Environmental Science and Technology 37 (2003), 434A–441A.

[6] Braungart M, McDonough W, Bollinger A. Cradle-to-cradle design: Creating healthy emissions – A strategy for eco-effective product and system design. Journal of Cleaner Production 15 (2007), 1337–1348.

[7] United Nations General Assembly (2015) Transforming Our World: the 2030 Agenda for Sustainable Development, A/RES/70/1. Available at: https://www.refworld.org/docid/57b6e3e44.html [accessed March 11, 2020]
[8] Kalmykova Y, Sadagopan M, Rosado L. Circular economy - From review of theories and practices to development of implementation tools. Resources Conservation and Recycling 135 (2018), 190–201.
[9] Ávila-Gutiérrez MJ, Martín-Gómez A, Aguayo-González F, Córdoba-Roldán A. Standardization framework for sustainability from circular economy 4.0. Sustainability 11 (2019), 6490.
[10] Korhonen J, Honkasalo A, Seppälä J. Circular economy: The concept and its limitations. Ecological Economics 143 (2018), 37–46.
[11] Pesce M, Tamai I, Guo D, Critto A, Brombal D, Wang X, Cheng H, Marcomini A. Circular economy in China: Translating principles into practice. Sustainability 12 (2020), 832.
[12] D'Adamo I, Falcone PM, Gastaldi M, Morone P. A social analysis of the olive oil sector: The role of family business. Resources 8 (2019), 151.
[13] Ladu L, Imbert E, Quitzow R, Morone P. The role of the policy mix in the transition toward a circular forest bioeconomy. Forest Policy and Economics 110 (2020), 101937.
[14] Morone P, Sica E, Makarchuk O. From waste to value: Assessing the pressures toward a sustainability transition of the Ukrainian waste management system. In: Innovation Strategies in Environmental Science, Elsevier, 2020.
[15] Morone P. The times they are a-changing: Making the transition toward a sustainable economy. Biofuels, Bioproducts and Biorefining 10 (2016), 369–377.
[16] Schot J, Geels FW Niches in evolutionary theories of technical change: A critical survey of the literature. Journal of Evolutionary Economics 17 (2007), 605–622.
[17] Svensson O, Nikoleris A. Structure reconsidered: Towards new foundations of explanatory transitions theory. Research Policy 47 (2018), 462–473.
[18] Markard J, Truffer B. Technological innovation systems and the multi-level perspective: Towards an integrated framework. Research Policy 37 (2008), 596–615.
[19] The British Standards Institution (2017) BS 8001:2017 Framework for implementing the principles of the circular economy in organizations.
[20] CEN-CENELEC Joint Technical Committee 10 on Energy-related products - Material Efficiency Aspects for Ecodesign (CEN-CLC/JTC 10) (2019) EN 45558:2019 General method to declare the use of critical raw materials in energy-related products.
[21] CEN-CENELEC Joint Technical Committee 10 on Energy-related products - Material Efficiency Aspects for Ecodesign (CEN-CLC/JTC 10) (2019) EN 45559:2019 Methods for providing information relating to material efficiency aspects of energy-related products.
[22] European Commission (2020) Circular Economy Action Plan. A European Green Deal. Available at https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en [accessed March 19, 2020].
[23] Ellen MacArthur Foundation (2015) Circularity Indicators. An Approach to Measuring Circularity. Available at:https://www.ellenmacarthurfoundation.org/assets/downloads/insight/Circularity-Indicators_Project-Overview_May2015.pdf [accessed March 11, 2020].
[24] Ellen MacArthur Foundation (2019) Circulytics - measuring circularity. Available at: https://www.ellenmacarthurfoundation.org/resources/apply/circulytics-measuring-circularity [accessed March 11, 2020].
[25] Enel Sp.A. (n.d.) CirculAbility Model. Available at: https://corporate.enel.it/en/circular-economy-sustainable-future/performance-indicators [accessed March 11, 2020].
[26] Skene KR. Circles, spirals, pyramids and cubes: Why the circular economy cannot work. Sustainability Science 13 (2018), 479–492.
[27] Kalmykova Y, Sadagopan M, Rosado L. Circular economy – From review of theories and practices to development of implementation tools. Resources, Conservation and Recycling 135 (2018), 190–201.
[28] D'Amato D, Droste N, Allen B, Kettunen M, Lähtinen K, Korhonen J, Leskinen P, Matthies BD, Toppinen A. Green, circular, bio economy: A comparative analysis of sustainability avenues. Journal of Cleaner Production 168 (2017), 716–734.
[29] Geisendorf S, Pietrulla F. The circular economy and circular economic concepts—A literature analysis and redefinition. Thunderbird International Business Review 60 (2018), 771–782.
[30] Prieto-Sandoval V, Jaca C, Ormazabal M. Towards a consensus on the circular economy. Journal of Cleaner Production 179 (2018), 605–615. Leal Filho W, Tripathi SK, Andrade Guerra JBSOD, Giné-Garriga R, Orlovic Lovren V, Willats J. Using the sustainable development goals towards a better understanding of sustainability challenges. International Journal of Sustainable Development and World Ecology 26 (2019), 179–190.

[31] Bjørn A, Diamond M, Owsianiak M, Verzat B, Hauschild MZ. Strengthening the link between life cycle assessment and indicators for absolute sustainability to support development within planetary boundaries. Environmental Science and Technology 49 (2015), 6370–6371.
[32] Rotmans J, Loorbach D. Complexity and transition management. Journal of Industrial Ecology 13 (2009), 184–196.
[33] Frantzeskaki N, Loorbach D, Meadowcroft J. Governing societal transitions to sustainability. International Journal of Sustainable Development 15 (2011), 19–36.
[34] Schot J, Steinmueller WE. Three frames for innovation policy: R&D, systems of innovation and transformative change. Research Policy 47 (2018), 1554–1567.
[35] Geels FW. Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study. Research Policy 31 (2002), 1257–1274.
[36] Schlaile MP, Urmetzer S. Transitions to Sustainable Development. In Leal Filho W. (Ed.). Decent Work and Economic Growth, Springer International Publishing, 2019.
[37] Pyka A. Dedicated innovation systems to support the transformation towards sustainability: Creating income opportunities and employment in the knowledge-based digital bioeconomy. Journal of Open Innovation: Technology, Market, and Complexity 3 (2017), 27.
[38] Cajaiba-Santana G. Social innovation: Moving the field forward. A conceptual framework. Technological Forecasting and Social Change 82 (2014), 42–51.
[39] Patterson J, Schulz K, Vervoort J, van der Hel S, Widerberg O, Adler C, Hurlbert M, Anderton K, Sethi M, Barau A. Exploring the governance and politics of transformations towards sustainability. Environmental Innovation and Societal Transitions, 24 (2017), 1–16.
[40] Sorrell S. Explaining sociotechnical transitions: A critical realist perspective. Research Policy 47 (2018), 1267–1282.
[41] Wesseling JH, Lechtenböhmer S, Åhman M, Nilsson LJ, Worrell E, Coenen L. The transition of energy intensive processing industries towards deep decarbonization: Characteristics and implications for future research. Renewable and Sustainable Energy Reviews 79 (2017), 1303–1313.
[42] Kivimaa P, Kangas H-L, Lazarevic D. Client-oriented evaluation of 'creative destruction' in policy mixes: Finnish policies on building energy efficiency transition. Energy Research and Social Science 33 (2017), 115–127.
[43] Rogge KS, Schleich J. Do policy mix characteristics matter for low-carbon innovation? A survey-based exploration of renewable power generation technologies in Germany. Research Policy 47 (2018), 1639–1654.
[44] Schot J. Confronting the Second Deep Transition through the Historical Imagination. Technology and Culture 57 (2016), 445–456.
[45] Walrave B, Raven R. Modelling the dynamics of technological innovation systems. Research Policy 45 (2016), 1833–1844.
[46] Rip A, Kemp R. Technological Change. In: Rayner S, Malone EL. (Eds) Human Choice and Climate Change, Battelle, Columbus, OH, 1998.
[47] Geels FW, Schot J. Typology of sociotechnical transition pathways. Research Policy 36 (2007), 399–417.
[48] Grin J, Rotmans J, Schot J. Transitions to Sustainable Development: New Directions in the Study of Long Term Transformative Change, Routledge, New York, 2010.
[49] Hosseinifarhangi M, Turvani EM, van der Valk A, Carsjens JG Technology-driven transition in urban food production practices: A case study of Shanghai. Sustainability 11 (2019), 6070.
[50] Kompella L. Barriers to radical ınnovations as stable designs: Insights from an IT case study. International Journal of Innovation Management 23 (2019), 1950047.
[51] Lin X, Sovacool BK. Inter-niche competition on ice? Socio-technical drivers, benefits and barriers of the electric vehicle transition in Iceland. Environmental Innovation and Societal Transitions 35 (2020), 1–20.
[52] Geels FW. Socio-Technical Transitions to Sustainability, in: Oxford Research Encyclopedias Environmental Science, Oxford University Press, 2018.
[53] Geels FW. Socio-technical transitions to sustainability: A review of criticisms and elaborations of the Multi-Level Perspective. Current Opinion in Environmental Sustainability 20 (2019), 1–15.
[54] International Organization for Standardization (2006) ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines.
[55] Corona B, Shen L, Reike D, Rosales Carreón J, Worrell E. Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics. Resources Conservation and Recycling 151 (2019), 104498.

https://doi.org/10.32933/ActaInnovations.36.1• ISSN 2300-5599 • © 2020 RIC Pro-Akademia – CC BY

[56] Lokesh K, Matharu AS, Kookos IK, Ladakis D, Koutinas A, Morone P, Clark J. Hybridised sustainability metrics for use in life cycle assessment of bio-based products: Resource efficiency and circularity. Green Chemistry 22 (2020), 803–813.
[57] Reap J, Roman F, Duncan S, Bras B. A survey of unresolved problems in life cycle assessment. Part 1: Goal and scope and inventory analysis. International Journal of Life Cycle Assessment 13 (2008), 290–300.
[58] Reap J, Roman F, Duncan S, Bras B. A survey of unresolved problems in life cycle assessment. Part 2: Impact assessment and interpretation. International Journal of Life Cycle Assessment 13 (2008), 374–388.
[59] Curran MA. Life Cycle Assessment: A review of the methodology and its application to sustainability. Current Opinion in Chemical Engineering 2 (2013), 273–277.
[60] Dreyer LC, Hauschild MZ, Schierbeck J. A framework for social life cycle impact assessment. International Journal of Life Cycle Assessment 11 (2006), 88–97.
[61] Guinée JB, Heijungs R, Huppes G, Zamagni A, Masoni P, Buonamici R, Ekvall T, Rydberg T. Life cycle assessment: Past, present, and future. Environmental Science and Technology 45 (2011), 90–96.
[62] Heijungs R, Settanni E, Guinée J. Toward a computational structure for life cycle sustainability analysis: Unifying LCA and LCC. International Journal of Life Cycle Assessment 18 (2013), 1722–1733.
[63] Heijungs R, Huppes G, Guinée JB. Life cycle assessment and sustainability analysis of products, materials and technologies. Toward a scientific framework for sustainability life cycle analysis. Polymer Degradation and Stability 95 (2010), 422–428.
[64] Campos-Guzmán V, García-Cáscales MS, Espinosa N, Urbina A. Life Cycle Analysis with Multi-Criteria Decision Making: A review of approaches for the sustainability evaluation of renewable energy technologies. Renewable and Sustainable Energy Reviews 104 (2019), 343–366.
[65] Hoogmartens R, Van Passel S, Van Acker K, Dubois M. Bridging the gap between LCA, LCC and CBA as sustainability assessment tools. Environmental Impact Assessment Review 48 (2014), 27–33.
[66] Yilan G, Kadirgan MAN, Çiftçioğlu GA. Analysis of electricity generation options for sustainable energy decision making: The case of Turkey. Renewable Energy 146 (2020), 519–529.
[67] You F, Tao L, Graziano DJ, Snyder SW. Optimal design of sustainable cellulosic biofuel supply chains: Multiobjective optimization coupled with life cycle assessment and input–output analysis. AIChE Journal 58, (2012), 1157–1180.
[68] Falcone PM, González García S, Imbert E, Lijó L, Moreira MT, Tani A, Tartiu VE, Morone P. Transitioning towards the bio-economy: Assessing the social dimension through a stakeholder lens. Corporate Social Responsibility and Environmental Management 26 (2019), 1135–1153.
[69] Yıldız-Geyhan E, Yılan G, Altun-Çiftçioğlu GA, Kadırgan MAN. Environmental and social life cycle sustainability assessment of different packaging waste collection systems. Resources Conservation and Recycling 143 (2019), 119–132.
[70] Millward-Hopkins J, Busch J, Purnell P, Zwirner O, Velis CA, Brown A, Hahladakis J, Iacovidou E. Fully integrated modelling for sustainability assessment of resource recovery from waste. Science of the Total Environment 612 (2018), 613–624.
[71] Antonino M, Gutiérrez TN, Baustert P, Benetto E. Implementation of Agent-Based Models to support Life Cycle Assessment: A review focusing on agriculture and land use. AIMS Agriculture and Food 3 (2018), 535–560.
[72] Niero M, Kalbar PP. Coupling material circularity indicators and life cycle based indicators: A proposal to advance the assessment of circular economy strategies at the product level. Resources Conservation and Recycling 140 (2019), 305–312.
[73] Elia V, Gnoni MG, Tornese F. Measuring circular economy strategies through index methods: A critical analysis. Journal of Cleaner Production 142 (2017), 2741–2751.
[74] Mesa J, Esparragoza I, Maury H. Developing a set of sustainability indicators for product families based on the circular economy model. Journal of Cleaner Production 196 (2018), 1429–1442.
[75] Parchomenko A, Nelen D, Gillabel J, Rechberger H. Measuring the circular economy - A Multiple Correspondence Analysis of 63 metrics. Journal of Cleaner Production 210 (2019), 200–216.
[76] Lazarevic D, Brandao M. Prospects for the circular economy and conclusions. in: Handbook of the Circular Economy, Edward Elgar, 2020.
[77] Korhonen J, Nuur C, Feldmann A, Birkie SE. Circular economy as an essentially contested concept. Journal of Cleaner Production 175 (2018), 544–552.
[78] Charonis G, Degrowth, steady state economics and the circular economy: Three distinct yet increasingly converging alternative discourses to economic growth for achieving environmental sustainability and social equity. in: World Economic Association Sustainability Conference, 2012.

[79] Ellen MacArthur Foundation (2015) Growth within: A Circular Economy Vision for a Competitive Europe. Available: https://www.ellenmacarthurfoundation.org/publications/growth-within-a-circular-economy-vision-for-a-competitive-europe [accessed June 6, 2020].
[80] Kovacic Z, Strand R, Völker T. The Circular Economy in Europe: Critical Perspectives on Policies and Imaginaries, Routledge, 2020.
[81] European Commission (2014) Towards a circular economy: A zero waste programme for Europe. Available: https://eur-lex.europa.eu/resource.html?uri=cellar:aa88c66d-4553-11e4-a0cb-01aa75ed71a1.0022.03/DOC_1&format=PDF [accessed June 6, 2020]
[82] Youn C, Kim SY, Lee Y, Choo HJ, Jang S, Jang JI. Measuring retailers' sustainable development. Business Strategy and the Environment 26 (2017), 385–398.
[83] Ruiz-Real JL, Uribe-Toril J, Gázquez-Abad JC, Valenciano J de P. Sustainability and retail: Analysis of global research. Sustainability 11 (2018), 14.
[84] Schindehutte M, Morris MH, Kocak A. Understanding market-driving behavior: the role of entrepreneurship. Journal of Small Business Management 46 (2008), 4–26.
[85] Ellen MacArthur Foundation (2020) The Covid-19 recovery requires a resilient circular economy. Available at:https://medium.com/circulatenews/the-covid-19-recovery-requires-a-resilient-circular-economy-e385a3690037 [accessed June 2, 2020].
[86] Bergek A, Jacobsson S, Carlsson B, Lindmark S, Rickne A. Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. Research Policy 37 (2008), 407–429.
[87] Hekkert MP, Suurs RAA, Negro SO, Kuhlmann S, Smits REHM. Functions of innovation systems: A new approach for analysing technological change. Technological Forecasting and Social Change 74 (2007), 413–432.
[88] Jacobsson S, Bergek A. Innovation system analyses and sustainability transitions: Contributions and suggestions for research. Environmental Innovation and Societal Transitions 1 (2011), 41–57.
[89] Hacking N, Pearson P, Eames M. Mapping innovation and diffusion of hydrogen fuel cell technologies: Evidence from the UK's hydrogen fuel cell technological innovation system, 1954–2012. International Journal of Hydrogen Energy 44 (2019), 29805–29848.
[90] van Welie MJ, Truffer B, Yap X-S. Towards sustainable urban basic services in low-income countries: A Technological Innovation System analysis of sanitation value chains in Nairobi. Environmental Innovation and Societal Transitions 33 (2019), 196–214.
[91] Sawulski J, Gałczyński M, Zajdler R. Technological innovation system analysis in a follower country – the case of offshore wind in Poland. Environmental Innovation and Societal Transitions 33 (2019), 249–267.
[92] Bilali H-E. Transition heuristic frameworks in research on agro-food sustainability transitions. Environment, Development and Sustainability 22 (2020), 1693–1728.
[93] Kushnir D, Hansen T, Vogl V, Åhman M. Adopting hydrogen direct reduction for the Swedish steel industry: A technological innovation system (TIS) study. Journal of Cleaner Production 242 (2020), 118185.

.

THE EU'S FARM TO FORK STRATEGY: MISSING LINKS FOR TRANSFORMATION

Sinead Mowlds
Cambridge Central Asia Forum, Jesus College, Jesus Lane
Cambridge CB5 8BL, United Kingdom, sinead.mowlds@cantab.net
https://orcid.org/0000-0002-5473-7783

Abstract
The Farm-to-Fork strategy, launched in May 2020, is the first attempt at a European-wide approach to food systems of this scale. The strategy sets ambitious targets and aims to create a 'fair, healthy, and environmentally friendly food system'. Yet, within the bounds of its own regulatory and legislative context (including the Green Deal, the Circular Economy Action Plan and the new Biodiversity Strategy 2030), the strategy falls short of recognizing key links in and between the food system. This review posits that the strategy and its targets do not adequately consider the importance of transforming agricultural practices for environmental outcomes; of agricultural practices for nutrition outcomes; nor the links between how we value nutrition along the supply chain, from farm to fork.

Keywords
food systems; food security; Green Deal; European Union; nutrition; agriculture.

Introduction

The Farm-to-Fork (F2F) strategy, launched on the 20th May 2020 is a first attempt at a European-wide approach to food systems [1]. The F2F strategy makes bold commitments and outlines actions to accelerate the achievement of a sustainable food system across Europe. The urgency of implementing the EU's vision for sustainable, resilient food systems was clear even in the earliest stages of the COVID crisis, which highlighted challenges and risks relating to food safety, traceability, and availability. The F2F strategy is encapsulated in the wider European Green Deal [2], launched in December 2019.

The European Green Deal is a roadmap to guide Europe towards becoming 'the first climate-neutral continent' – an ambition that is only conceivable thanks to the cross-border agreements facilitated by the Union's common institutions. The Green Deal has three main objectives for a new growth strategy: zero emissions of GHG by 2050; decoupling economic growth from resource use; and leaving no person nor place behind. It sends a strong and clear message: the EU is on the path to transforming its economic and commercial landscapes. However, the Green Deal cannot be achieved without the implementation of several interconnected strategies including the new Circular Economy Action Plan [3], Biodiversity Strategy 2030 [4], and the F2F strategy.

The F2F strategy's aim 'for a fair, healthy and environmentally-friendly food system' through an approach that renews 'how Europeans value food sustainability', can be unpacked by considering concepts of food system, food and nutrition security, interdependence and value.
The FAO (2018) defines a food system as one encompassing:

> "*the entire range of actors and their interlinked value-adding activities involved in the production, aggregation, processing, distribution, consumption and disposal of food products that originate from agriculture, forestry or fisheries, and parts of the broader economic, societal and natural environments in which they are embedded*" [5].

Until this year, the commonly accepted conceptualisation of food and nutrition security encompassed just four components: *availability, access, utilisation, and stability*. On the 25th June 2020, the High Level Panel of Experts[1] (HLPE) produced their 15th report on food security and nutrition for the Committee on World Food Security [6]. In this report, two components were added to the concept of food security: *agency and sustainability*.

[1] The High Level Panel of Experts on Food Security and Nutrition, a science-policy interface of the UN Committee on World Food Security (CFS), was created in October 2009 as an essential element of the CFS reform.

https://doi.org/10.32933/ActaInnovations.36.2• ISSN 2300-5599 •

Agency*: capacity of individuals or groups to make their own decisions about what foods they eat, what foods they produce, how that food is produced, processed and distributed within food systems, and their ability to engage in processes that shape food system policies and governance.*

Sustainability*: long-term ability of food systems to provide food security and nutrition in a way that does not compromise the economic, social and environmental bases that generate food security and nutrition for future generations.*

These additional concepts, along with the FAO (2018) definition of a food system and its interlinkages, provide space for considering the intricate interdependencies between the food system's components; and emphasise the need for policies that appreciate the interconnectedness of different systems and sectors to achieve 'regenerative, productive and resilient food systems'. Further, the definition of 'agency' acknowledges individuals as citizens (e.g. recognising a group's agency), rather than as consumers only, thus providing space for interdependencies at structural, spatial, and temporal levels to be considered (e.g. future generation's welfare) [7].

Further, the HLPE report highlights the need for a rights-based approach to underpin this framework, and 'widen our understanding of food security and to adopt a food systems framework'. Action Aid (2019) argue that a just transition must include a food system that not only benefits 'nature and the climate but also ensures the right to food for all' [8]. The F2F suggests alignment with these concepts in its aim for a 'fair' system to be achieved through a 'just transition'.

Although the strategy represents a starting point – a roadmap for future legislation – its vision will define the outcomes and thus the F2F aim to renew 'how Europeans value food systems' is crucial. Indeed, the fundamental values associated with food systems will influence the approach and methods chosen, which 'define the logic of the appraisal process and influence the output' [7]. Meaning, if the value of sustainability is measured within a market based approach then the tendency will be to measure value based on individual preference, as a consumer. On the other hand, a justice-driven approach will tend to consider value from the perspective of an individual's values as part of a community, or as a citizen [7]. The former focusses on improved efficiency, technological innovation, free trade, and pricing mechanisms, whereas the latter provides space for interdependencies [9, 10].
For policy makers, such interdependence can mean facing the fragile balance of trade-offs between differing structural and temporal objectives, such as between short-term agricultural development or long-term environmental preservation, or competition for the use of natural resources. Further, interdependence means decisions made by one agent can affect another's choices, which can lead to conflict over the use of natural resources [7, 11]. Yet, an efficient sustainable food system needs policy coherence across these different objectives (including health and agriculture) [12], as fragmented governance can lead to policy inertia and threaten progress [6]. Further, Benton & Baily (2019) argue that a sustainable food system is one that reframes efficiency so that it means food systems deliver profits, healthy diets, and a healthy planet, rather than trade, yield (increasing), and price (decreasing) policies [13].

In theory, the F2F strategy aligns with these concepts and approaches to achieving a 'fair, healthy, and environmentally-friendly food system', but the depth of the systems approach is unclear. It recognises the need to ensure 'agency' of individuals through initiatives to empower individuals (referred to interchangeably as consumers and citizens) and aims for a 'just transition'. Yet the inter-linkages between the stages and components of the food system are not always explicit.
This article aims to gain further insight into the F2F strategy by providing an overview of the strategy and its intended and potential environmental, social, economic and policy impacts. Then, in the context of the above conceptualisation of an efficient, coherent and sustainable food system, section II considers F2F's approach to agriculture and nutrition. Specifically, the article considers how these components of the food system might be redesigned to align with the new conceptualisation of food security.

Methods
This article was informed by a review of grey literature, including key policy documents and data relating to the European Green Deal, namely the F2F strategy, the Action Plans for the Circular Economy 2015 and 2020, and the Biodiversity Strategy 2030. Analyses were based on three main frameworks. First, as described in the

introduction, the analyses relies on the new Sustainable Food System Framework developed in the HLPE's 15th report Food security and nutrition: building a global narrative towards 2030. Second, the FAO framework for sustainable food systems [5] was the foundation for the critical analysis of the F2F approach. This definition allows for the interlinkages between the food systems various components to be considered at policy level. Third, based on concepts of policy coherence for development – for which the EU is the only region in the world to have a legal commitment in this regard, enshrined in the Treaty on the Functioning of the European Union – which can be considered achieved when policy actions across sectors and stakeholders are actively aligned towards meeting agreed objectives [12].

To inform trend analyses, data were sourced from the Eurostat database: (https://ec.europa.eu/eurostat/data/database). Latest available data were used where possible. Because the EU is an aggregate of countries yet is not static (e.g. expansion or withdrawal of members), some datasets retroactively apply a constant membership definition (and are hence subject to revision) but others describe a different population at different times. This leads to the 'EU Changing Composition' aggregation. Because not all data is aggregated for the newly composed EU (EU27, excluding the UK), for consistency, the EU Changing

Composition aggregation (as of June 2020) was used throughout. For Figure 1 data were used from 2005 only due to missing data for some years (2001 and 2004). Simple linear trend analyses, data was extrapolated to understand Business as Usual (BAU) and F2F target trajectories towards 2030. For Table 2, data were sourced from the 2016 report by the European Community Supported Agriculture (CSA) Research Group: Overview of Community Supported Agriculture in Europe.

The data used for Map 1 are sourced from Eurostat and based on the indicator 'overweight'. The indicator reflects the share of overweight within the population based on their body mass index (BMI). BMI is defined as the weight in kilos divided by the square of the height in meters. People aged 18 years or over are considered obese with a BMI equal or greater than 30. Other categories are: underweight (BMI less than 18.5), normal weight (BMI between 18.5 and less than 25), and pre-obese (BMI between 25 and less than 30). The category overweight (BMI equal or greater than 25) combines the two categories pre-obese and obese.

Map 2 data were sourced from Eurostat based on the indicator 'estimated soil erosion by water - % of area affected by severe erosion rate'. The indicator, expressed as a percentage of the total non-artificial erosive area in the country, estimates the soil loss by water erosion processes (rain splash, sheetwash and rills) and gives an indication of the area under risk of being affected by a certain rate of soil erosion (severe soil loss, E > 10 tonnes/hectare/year). Where there is no area of land that is in risk of being subject to soil erosion by water of more than 10 tonnes per hectare, a country will have a zero value. Soil erosion may still be occurring in areas of those countries, but at a rate of less than 10 tonnes per hectare.

Limitations

Missing data limited the potential for historic trends, and of a comprehensive comparative analysis (e.g. number of CSAs in member states). Further, the indicators used to establish levels of overweight, or environmental degradation are useful as proxies only, and only reflect a small slice of the nutritional or planetary health stories.

I. Overview

a. An ambitious opportunity

The F2F strategy is a first attempt at developing a European-wide approach to creating sustainable food systems, which in itself is ambitious considering the diversity of institutional, geographic and demographic contexts across the EU member states. It allows 27 countries to act collectively and in harmony towards a 'fair, healthy, and environmentally-friendly food system' based on three main components:

1. Building the food chain that works for consumers, producers, climate and the environment
2. Enabling the transition
3. Promoting the global transition

The EU is uniquely positioned to leverage its institutional capacity to support progress towards sustainable food systems. Although other regional powers exist (e.g. APEC, ASEAN, EAEU, MERCOSUR, etc.) these tend to be concentrated on trade and economics and lack the common institutional foundation and frameworks within which the European Union operates. The EU institutions provide a judicial system to hold members accountable, and a space to harmonise decisions across member states. This is crucial for decisions relating to environmental

https://doi.org/10.32933/ActaInnovations.36.2• ISSN 2300-5599 •

challenges, as each country's boundaries do not reflect the boundaries of the ecosystems within which they operate.
Further, the EU provides a space for shared knowledge, and collaborate in cross-country research and development. F2F promises to continue in this line, identifying Research and Innovation as 'key drivers' in accelerating a just transition to sustainable food systems, with EUR1 billion to be spent this year for the Green Deal priorities under Horizon 2020. Horizon 2020 was the EU's largest research and innovation programme to date, with around EUR 80 billion available every seven years to support the implementation of the Innovation Union [14], representing roughly 27% of total EU funding for R&D over a seven year period (see appendix 2). Between 2014 and 2016, 65% of these financial contributions were related to sustainability (surpassing its 60% target) and 28% were related to climate challenges (falling short of its 35% target) [15]. Horizon Europe (H2020's successor) proposes to spend EUR 10 billion on sectors relating to food systems, such as the bioeconomy and nature-based solutions to agri-food, representing 10% of Horizon Europe's budget until 2027 [16].

The strategy addresses sensitive issues, clearly acknowledging the risks and concerns expressed by the Union's citizens. For example, it acknowledges - without vilifying – the specific role of retailers and processers, and marketing, namely in influencing consumer's dietary choices and the shaping of the food supply chain. Further, when the potential for biotechnology (including GMOs) is raised, the Commission is quick to add that these may play a role only if they are 'safe for consumers and the environment while bringing benefits for society as a whole'.

The strategy's targets are ambitious, particularly considering the current trends and trajectories. These include to:

- reduce the overall use and risk of chemical pesticides by 50% and the use of more hazardous pesticides by 50% by 2030.
- enhance provisions on integrated pest management and promote greater use of safe alternative ways of protecting harvests from pests and diseases.
- reduce nutrient losses by at least 50%, while ensuring that there is no deterioration in soil fertility, with a view to reducing the use of fertilisers by at least 20% by 2030.
- achieve at least 25% of the EU's agricultural land under organic farming by 2030
- revise animal welfare legislation

The ambitious nature of these targets can be exemplified by the fact that the EU would need to increase by nearly 2.5 times its current rate of growth to achieve the target of 25% of agricultural land under organic farming.

Figure 1 below shows the EU's trend in a business as usual approach vs the trajectory required to achieve the target. In the BAU scenario, just 10.3% of EU agricultural land would be under organic production by 2030. This target prompts member states to double the speed of growth from 5% between 2005 and 2018 to an 11% annual growth rate between now and 2030, to reach the 25% F2F target (see appendix 1).

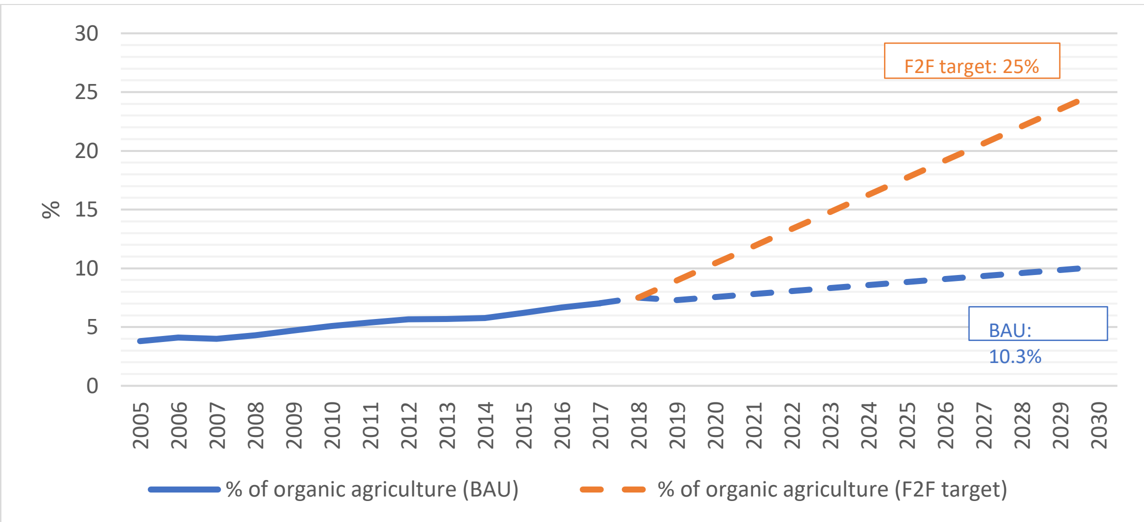


Fig. 1. Trend in agricultural land under organic farming in the EU 28 (2000 – 2030). *Source: Eurostat and author's calculations*

https://doi.org/10.32933/ActaInnovations.36.2• ISSN 2300-5599 •

b. Impact

Globally, estimates suggest that moving towards sustainable food and agriculture systems could generate new economic value of more than EUR 1.8 trillion [17]. The agriculture, construction, and the food and drinks sectors in Europe - all highly dependent on nature - generate more than EUR 7 trillion per year. At the same time, in the EU, as of 2017, 950,000 deaths were associated with unhealthy diets [18]. Through F2F, the EU aims to leverage the economic potential of a transition towards more sustainable systems and reduce the health costs associated with unhealthy diets. The EU specifically promises the following impact:

Table 1. Economic, social, and environmental impacts of the Farm to Fork strategy. *Source: European Commission Farm to Fork Strategy*

Economic and social impact for farmers [19]	Economic impact of biodiversity [20]
• Higher returns for farmers and food producers by linking sustainable production methods to premium consumer demand • A stronger role in the supply chain • New business opportunities (e.g. plant protein sector or bioeconomy) • Lower costs through higher productivity and reduced inputs, led by innovation, technological and digital solutions. • Stronger connection with consumers • Additional export opportunities through new global markets	• Increased annual profits of the seafood industry by more than €49 billion by conserving marine stocks • Save the insurance industry around €50 billion annually through reducing flood damage losses by protecting coastal wetlands • Increased employment through directly and indirectly related jobs

These intended impacts align with the F2F and HLPE's objectives, particularly in increasing farmers' agency by ensuring a 'stronger role' and bargaining power in the supply chain. However, the stated impacts are largely focussed on the short-term goals and maintains a focus on 'lower costs through higher productivity' to be driven by technological solutions. Further, the concept of longer-term goals is limited to ensuring the EU's competitive capacity in transitioning and building resilience to future pandemics and diseases. Thus, the F2F strategy diverges from the concept of sustainability by overemphasising short-term economic goals.

Transitioning to a food systems approach will also have an impact on national policymaking approaches, as policymakers will need to collaborate with stakeholders from a variety of backgrounds and across different institutional levels. The HPLE report 2020 identify four key policy shifts required to achieve sustainable food systems:

1. Recognise the need for radical transformation of food systems
2. View food and nutrition security as a system interconnected with other systems and sectors
3. Focus on hunger and all forms of malnutrition
4. Recognise food and nutrition security as context specific and requiring diverse solutions.

The report also emphasises the importance of coherent governance and research, including investing in public research. This can mean creating inter-governmental working groups or committees and engaging in participatory planning processes. The Dutch government, for example, is leading the way by institutionalising this systemic approach in their Ministry of agriculture, nature, and food quality, which is currently experimenting with 'circularity in agricultural production' [21]. Further data relating to the needs of individuals and communities and the environmental context, need to be created or improved upon, particularly for transparency purposes. Specifically, as outlined in the F2F strategy, spatial data can play a key role in informing effective decisions for agricultural production. Aligning with global standards and agreements, such as incorporating the UN's SEEA into national accounting systems can also help leverage momentum and garner political support and investment.

Policy makers will also need to consider programmes and initiatives that encourage systemic, transformative (albeit incremental) shifts. Introducing or strengthening the right to food at national level may provide the basis for this transformational shift and needs to be enshrined in national legislation. The rights-based approach, for

https://doi.org/10.32933/ActaInnovations.36.2• ISSN 2300-5599 • © 2020 RIC Pro-Akademia – CC BY

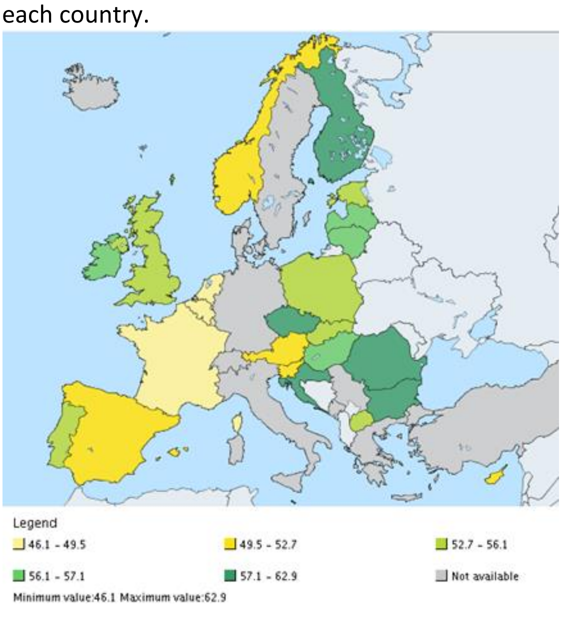
example, might mean providing nature with rights of its own, both legislatively and/or in institutional decision-making processes [22].

Further, in dealing with an EU-wide approach, the importance of context-specific solutions is clear in the differing needs, legislative set-ups, and ecoregion types across the member states. For example, supporting shorter food supply chains would look quite different depending on the country context. The table below highlights the significant range in terms of the number of ‘community supported agriculture’ (CSA) groups across 21 countries in Europe. CSA is defined as “a direct partnership between a group of consumers and producer(s) whereby the risks, responsibilities and rewards of farming activities are shared through long-term agreements. Generally operating on a small and local scale, CSA aims at providing quality food produced in an agroecological way.” It is considered as one way of categorising local food markets by the European Parliamentary Research Service. Countries such as Serbia, Ireland and Greece may need policies to support awareness and behavioural change whereas places like France and Belgium may benefit from policies that support broader access through improved infrastructure.

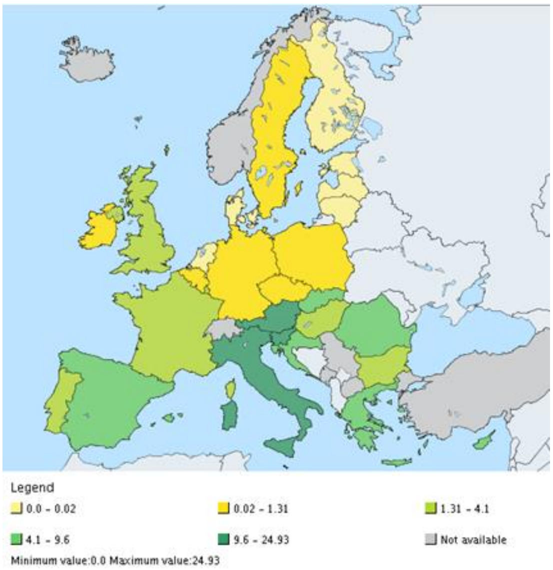
Table 2. Number of local food markets in 21 European cities. *Source: European CSA Research Group (2016): Overview* of Community *Supported Agriculture in Europe, available online: https://www.accesstoland.eu/IMG/pdf/overview-of-community-supported-agriculture-in-europe-f.pdf*

Country	**Number of CSA groups**	**Country**	**Number of CSA groups**
1. France	2000	12. Croatia	20
2. Belgium	138	13. Romania	15
3. Italy	104	14. Hungary	12
4. Germany	92	15. Sweden	12
5. United Kingdom	80	16. Finland	10
6. Spain	75	17. Slovakia	10
7. Switzerland	60	18. Poland	8
8. Netherlands	47	19. Greece	7
9. Norway	35	20. Ireland	7
10. Austria	26	21. Serbia	2
11. Czech Republic	23		

The same applies for nutrition-related policies where the percentage of population overweight, for example, varies significantly from one country to the next as shown in Map 1, below. Map 2 further highlights this point by showing the diversity in terms of soil erosion across EU member states, which should influence agricultural and environmental policies in each country.



Map 1. Percentage of overweight adults across EU member States. *Source: Eurostat, % of population aged 18 or over, 2017*



Map 2. Percentage of soil erosion by water pf total non-artificial erosive area.
Source: Eurostat, % of area affected by severe erosion rate

Finally, for an efficient sustainable food system, policy coherence needs to be applied across different sectors (including nutrition and agriculture). Hawkes (2017) [12] argues that to create policy coherence, the question ‘coherence for what?’ must be answered. In this case, the response is: a fair, healthy, and environmentally friendly food system. Benton & Baily (2019) argue that a sustainable food system is one that reframes efficiency; and develops policies that aim for food systems to deliver profits, healthy diets, and a healthy planet, rather than trade, yield (increasing), and price (decreasing) policies [13]. Further, the new Circular Economy Action Plan focusses on ‘eco-design’, highlighting that 80% of environmental impacts are determined at the design phase, underlining the importance of considering sustainability and health outcomes in the earliest stages of the system in question [3].

Based on these intended impacts and the four key policy shifts required, and in line with a just transition, the following section explores in greater detail what these transformations might look like for two components of the food system: agriculture and nutrition.

II. <u>‘Redesigning’ agriculture for nature and nutrition</u>

Making food production sustainable means moving beyond current agricultural practices to transformative practices that consider long-term changes and future generations. The F2F strategy proposes solutions focussed on reducing carbon emissions and increasing yields, rather than systemic alternatives that encompass broader goals such as ecosystem health. A sustainable approach to ‘designing’ healthy and environmentally sound food might start at the agricultural production stage. This would need to consider what food is being produced and how it is being produced to achieve both environmental and nutrition objectives. In this approach, agriculture can be considered as part of the landscape, an activity that is ‘growing nature’ [23], that produces nutritious food and allows biodiversity to thrive, rather than treating nature as an asset only. This requires a shift in how we think about agriculture and its primary stakeholders (farmers). Together, these considerations would align with a food system that comprehensively bolster agency and sustainability.
Similarly, useful and necessary measures to help consumers navigate a confusing food landscape are outlined in the F2F strategy but the strategy focusses more on the consumption side of nutrition and good health than it does on the production or design stage. The F2F strategy aims to empower consumers to make informed decisions for healthy diets, to support accountability, avoid greenwashing and tackle food fraud. Measures include a harmonised and mandatory ‘front-of pack’ labelling (e.g. on nutrition and environment, and potentially animal welfare); and engaging with the private sector to seek commitment to reformulate food products in line with healthy and sustainable diets, and to adapt marketing and advertising strategies to consider the needs of the most vulnerable. This is the first time such comprehensive measures will be taken at a regional scale and

will significantly increase a consumer's agency. But failing to consider agriculture in the 'design' stage of the food system for nutrition and health, limits the individual's agency for example to consider the food system in terms of how food is produced and processed, in line with the objectives of empowering citizens and bolstering their agency. Finally, it's important to note that for a just transition, the burden of change should not be disproportionately be placed on the consumer which may happen if policies overemphasise efforts relating to the consumption component of the food system.

The following sections consider what it might mean to 'design' sustainable food systems, from measurements to practices and research to processing in the F2F context.

a. Agricultural productivity, nature as a stakeholder, and farmers as custodians

One way of 'redesigning' agricultural production is by re-evaluating the way we measure and value the components of the food system and its stakeholders.

First, rather than measuring agricultural productivity in terms of yield outputs, measurements could focus on system productivity, valuing public health and sustainability over availability of cheap and large amounts of food. Agricultural productivity is currently measured largely based on yield output and trade factors. Benton and Bailey (2019) [13] highlight the inefficiency of current food systems by estimating efficiency levels of - at most - 41% (on an energy basis) efficient if the efficiency is based on the amount of food grown to feed people. They outline how the current understanding of efficient agricultural systems are at odds with today's reality and point to the 'paradox of productivity' in the rising waste at every step of the value chain, the public health impacts and environmental degradation of our current food systems. Indeed, the agricultural production stage of the food process produces 9 million tons of food waste on farms (i.e. food loss) [24].Thus, the authors propose moving away from the classic Total Factor Productivity (TFP) measurement of efficient food production, based on labour, capital, land and chemicals to consider the Total System Productivity (TSP). They do this by building off the concept of 'Total Resource Productivity', which includes natural capital, and further capture healthcare costs associated with agriculture, such as air pollution or dietary-related ill health and waste-disposal costs. Further, rather than measuring yield as a primary output measure productivity would be measured based on the number of people undernourished. This approach aligns with the EU's aim to 'renew' how Europeans value food sustainability and systems, yet such transformation is absent from the F2F strategy.

Second, another way of shifting the paradigm towards agriculture practices based on the needs and context of its ecosystem, is to consider nature as a stakeholder with rights of its own [22]. This requires rethinking how we value the environment, going beyond the perception of nature as a set of distinct and separate "goods and services". Reducing nature to a fragmented set of privatised and monetised commodities considers nature as something to consume rather than considering key spiritual, cultural, or social values which constitute the fabric of societies across the world. The World Wildlife Fund 2016 Report promotes progress made by the by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services in reconsidering how we value nature which 'takes valuing nature beyond simply assigning a dollar figure and recognizes other knowledge systems, for example those of local communities and indigenous peoples' [25]. The EU has already pioneered in the sphere: in October 2017, for the first time, the rights of nature were institutionalised at regional level, when the EU Economic and Social Committee (EESC) voted to adopt Opinion Nat/712. However, individual countries around the world have gone even further, recognising these rights in the constitution (e.g. Ecuador in 2008), and providing legal guardians to represent nature. Although challenges would arise from the varying institutional and legislative contexts across member states, taking this approach has the potential to expedite the EU's leadership in terms of transformative action for sustainable systems.

Third, the F2F strategy states that farming practices that 'remove CO2 from the atmosphere contribute to the climate neutrality objective and should be rewarded' - a good indication for farmers wanting to transition towards more sustainable practices. There are several strong elements in the strategy pointing to support for farmers and fishers, and on the essential nature of their work. In line with the idea of a just transition, supportive language is used through the document, namely to 'guarantee a decent income allowing them [farmers] to provide for their families and withstand crises of all kinds', to improve targeting of income support based on needs and outcomes, and to increase farmers' bargaining power by helping farmers and fishers to 'strengthen their position in the supply chain'. At the same time, F2F calls on farmers to 'transform production methods more quickly' and make best use of nature-based solutions and technological solutions. However, whilst support for reduced emissions is made clear, support for 'transforming' production methods is not made explicit. Further, the 'farmer'

https://doi.org/10.32933/ActaInnovations.36.2• ISSN 2300-5599 • © 2020 RIC Pro-Akademia – CC BY

is framed as being a producer of food only, rather than a custodian of nature. Although it is worth noting, at the strategy launch press conference, Timmerman lauded farmers and fishers as 'stewards' of our land and sea. Yet, farmers can support healthy soil, enhance biodiversity, wildlife, and provide nutritious and safe food. This is an essential and highly important role in society and support offered should tailor to the various responsibilities and subsequent interests of a custodian of the land or sea. Custodianship of land has been reflected legislatively in several countries around the world. For example, in 2014, providing rights to a river in New Zealand settled a 140-year old dispute between Maori tribes and the Crown. The river now has accountable, legal guardians — one from each disputing party [26]. Such an approach encourages participatory policymaking and leads to policies with structural, spatial, and temporal considerations — such as future generations and broader understandings of ownership [10]. It would bolster accountability and sustainability of the F2F strategy, by promoting participatory and interconnected approaches.

b. Agricultural practices: going beyond carbon emission solutions to 'growing nature'

The F2F target of reaching 25% organic farming in Europe is a significant step towards sustainability, potentially reducing damage to soils, wildlife and human health. Diverse and intraspecific ecosystems are at the basis of sustainable agricultural practices, which includes sustainable soil management to provide crops with the micro and macro-nutrients for a complete diet [27]. An agricultural practice that works in harmony with its eco-system must go beyond organic to include diversity at the 'output' and 'outcome' stages, meaning a diverse array of contextually appropriate crops and measures designed to increase food security and maximise ecosystems health.

The EU Biodiversity Strategy 2030 aims to 'bring nature back into our lives'. This should include bringing nature back into agriculture. Both agriculture and nature exist and prosper in complex systems; dynamic, chaotic, and interdependent, in which interactions are nonlinear. Neither can be understood, nor protected, by looking at component parts and policy and planning need to reflect this complexity. Applied to agriculture, this means practices should happen in harmony with local ecosystems, producing more nutrient-rich and flavourful food that promotes biodiversity growth in the region rather than depletes it.

Nature-based solutions (NBS) has emerged as one concept, present in multiple EU policy instruments, for practices that contribute to long-term health and well-being of people and planet [28]. For the EU Commission, such solutions 'bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions' [29]. The F2F strategy includes some NBS, such as a brief mention of agroecology, or as one of the 'transformational' practices that farmers can undertake to achieve F2F's goals. However, as mentioned previously, the F2F support mechanisms and targets tend to emphasise current agricultural practices rather than transformational ones. This is perhaps most visible in the absence of regenerative approach (to agriculture or other sectors) as a solution, despite this being a key component of the HLPE's conceptualisation of sustainability in food systems. NBS offer a diversity of solutions, from green urban infrastructures for improved health to bolstering coastal mangroves to reduce risks from natural disasters. In terms of agriculture, NBS include agroecological practices such as agroforestry, which can have profound positive effects for environmental, social and health goals. They can affect the environment by intercepting sunlight, reducing crop evapotranspiration, improving soil water-holding capacity and water infiltration, and enhancing carbon storage and biodiversity, and even lowering ambient temperatures. It fosters resilient livelihoods and communities, through alternative sources of income, increased availability of diversity of dietary needs, helps reduce air pollution (e.g. from dust) and provides a source of medicine [30]. Yet, depending on the underlying values, NBS will be more or less effective; if the F2F implementation is based narrowly on market driven approaches and cash flows, then this could undermine transformational progress namely by relying on 'weak sustainability' which allows for substitution of different forms of capital rather than long-termer approach which considers nature as non-substitutable [31]. To avoid this, policies can explicitly align objectives with the NBS goal of improve capacity to manage multiple objectives in complex socio-ecological systems. The F2F strategy would benefit from emphasising NBS and the interdependence of the food system's components, from agriculture and nature to agriculture and nutrition.

c. The links between agriculture and nutrition

The link between health outcomes and agriculture are absent from the strategy, yet, *what* is being produced – and *how* – will determine what is made available on the shelves for consumers. The drive for cheaper and more

https://doi.org/10.32933/ActaInnovations.36.2• ISSN 2300-5599 •

abundant food since the 1950s has seen food systems become reliant on a handful of crops mainly to feed increasing livestock; and has forged agricultural practices designed for high-yielding, energy-dense commodities to the detriment of nutrient-rich fruits and vegetables. Currently, 76% of the world's crop calories now come from just eight crops - wheat, rice and maize (representing 50% of crop calories), sugar, barley, soy, palm and potato [13, 32]. This lack of diversity in agriculture has led to widespread environmental degradation, namely a 58% decline in abundance of species on the planet since the 1970s [25]; and to a growing malnutrition burden as food manufacturers formulate products derived from low cost high-calorie commodities which contributes to the growth of obesogenic processed foods [13]. Globally, healthcare costs from inadequate diets are estimated to exceed 5% of GDP (this is a conservative figure, as of 2013) [33]. Figure 2's panels A and B, below, demonstrate this incoherence in global food systems by highlighting the discrepancy between what is being produced (i.e. made available to consumers) in contrast with the recommended dietary intakes.

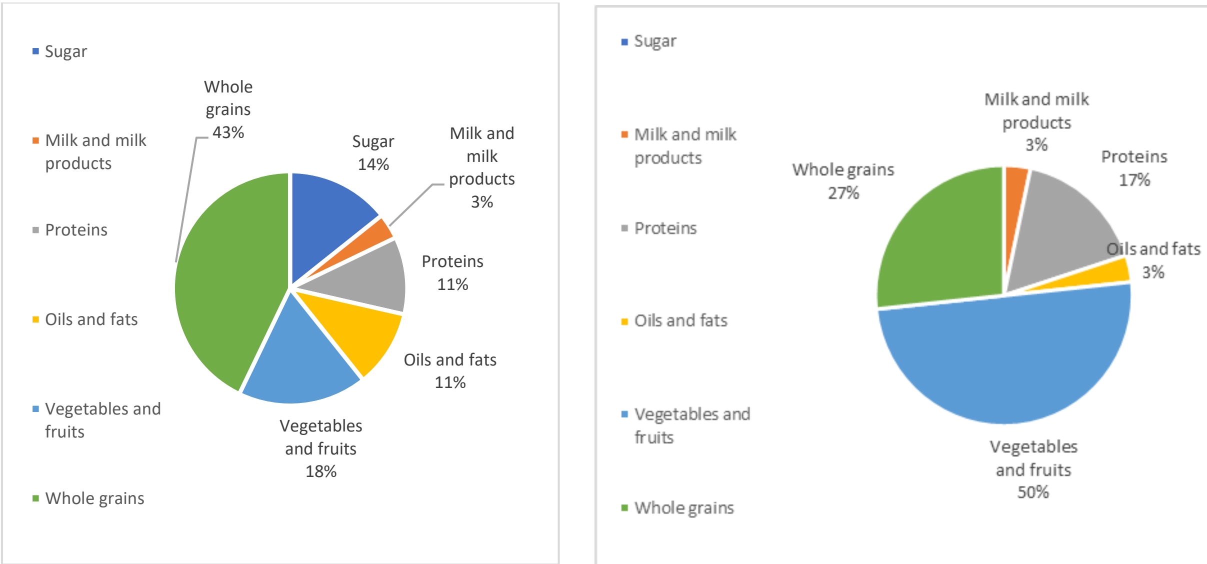


Fig. 2. What global food systems are producing vs nutritional requirements

Fig. 2a. Current production (2011 FAO data) Fig. 2b. Recommended diet (based on Harvard Healthy Eating Plate model)

Source: KC KB, Dias GM, Veeramani A, Swanton CJ, Fraser D, Steinke D, et al. (2018) When too much isn't enough: Does current food production meet global nutritional needs? PLoS ONE 13(10): e0205683. https://doi.org/10.1371/journal.pone.0205683; Unit of measurement: number of servings / person / day; inspired by Tim Benton's guest lecture for the Food System Academy (http://www.foodsystemsacademy.org.uk/videos/Tim-Benton.html)

By not considering the links between agriculture outputs and nutrition, initiatives stemming from the F2F strategy may continue in this line of emphasising quantity and affordability of food rather than quality. To overcome the overweight and obesity pandemic, the HLPE call on the agriculture sector to engage with the health and environmental sectors and ensure nutrition-driven and environmentally sustainable policies. Thus, the 'design' stage of a healthy diet needs to be explicitly considered from the agricultural production stage of the food system in order to ensure nutritional security for today's citizens as well as the future generations.

Further, the F2F strategy acknowledges that a resilient food system needs robust local food systems, and commits to '*reducing dependence on long-haul transportation*'. This is a small first step in supporting local food markets. Although empirical research is lacking in this area, links have been made between improved nutrition and access to local food markets due to the availability of fresher, more nutrient-dense and generally less processed foods than in supermarkets [34]. For improved nutrition to be linked with local markets, those markets need to be providing fresh, healthy food where consumers make different choices based on this newly available food. The F2F strategy somewhat addresses the issue of consumer choice by tackling issues such as nutrition labelling, but again, focuses largely on the consumption side rather than designing systems which incorporate local food markets. Shorter supply chains are mentioned just once in the strategy, despite the EU Parliament calling on the European Commission to '*propose the adoption of instruments to support and promote farmer-managed food supply chains, short supply chains and farmers' markets*' [35]. Although the definition of 'local food system' varies – it can include factors such as population density, accessibility, closeness of producer and

Consumer, etc. – common challenges and relevant policy measures have been identified. Indeed, several barriers to the development of short food supply chains exist, including the administrative and regulatory burden (especially for smallholder farmers) lack of knowledge and skills (e.g. entrepreneurial), and access to land (e.g. due to high prices) and bank loans can prevent young farmers from engaging, although they are more willing to engage in direct sales. Policy measures to resolve these issues could include adapting regulation, improving access to services, and enhancing knowledge transfer, advisory and training services [35]. Whilst the F2F strategy includes a focus on 'advisory services, data and knowledge sharing, and skills' no mention is made of how these will support shorter food supply chains. The strategy would benefit from making this explicit and including indicators on the number of local food markets available.

Finally, another structural opportunity missed for improved nutritional outcomes lies in the F2F's disproportionate focus on the environmental component of sustainable diets. For example, the strategy commits to making food procurement sustainable by reinforcing standards in canteen catering contracts, and reviewing the EU school scheme to 'enhance its contribution to sustainable food consumption and in particular to strengthen educational messages on the importance of healthy nutrition, sustainable food production and reducing food waste'. Promoting green procurement is an excellent goal gearing the EU member states towards transformation, particularly considering the EU institution public authorities' purchasing power represents 14% of the EU GDP, or roughly EUR 1.8 trillion [36]. Making institutional food procurement chains more sustainable should not only mean making them more environmentally sound, but also ensuring they provide the nutritious and safe food required. This is particularly relevant in the context of hospitals, care homes, and schools across Europe, where the provision of food can be motivated by price, rather than focussing on the nutritional value of food as part of the immune-boosting and healing processes. Most hospitals in Europe are still providing unhealthy and unappealing meals, rather than fresh, culturally appropriate and nutritious foods [37]. Yet, poor nutrition can impair the production and activity of immune cells and antibodies [38]; this is especially relevant in the context of a pandemic like COVID-19 which has highlighted the urgency of adequate nutrition for strong immune systems, particularly amongst society's more vulnerable communities (e.g. care homes) [39]. Sustainable food procurement for healthy diets could include measures to ensure locally sourced, diverse food as well as minimum nutritional requirements, in line with short food supply chain goals.

d. Nutrition research and guidelines

The EU Commission will 'seek commitments from food companies' relating to 'reformulating food products in line with guidelines for healthy sustainable diets' and will create nutrient profiles to help inform consumers. First, it is unclear which guidelines will be used to inform this crucial component of the strategy. Second, when nutrition is mentioned in the strategy, the focus is on improved diets through reducing fats, sugars, and salts, rather than increasing the diversity of nutritional intake and available healthy foods. Further, policy coherence and coordination relating to food and nutrition research and innovation is weak, and there is a lack of data and knowledge pertaining to investment amounts [40]. Yet, the F2F strategy makes no commitment to ensure prioritisation of research for nutrition – research that, for example, might link agricultural practices to nutritional outcomes. This could be partially addressed by improving the data, for example, by creating a central inventory of food and nutrition security research and innovation initiatives across member states [40].

Further, commitments from retailers, distributors and other stakeholders need to be transparent and based on a solid evidence-base. Similarly, to the F2F's efforts to avoid greenwashing, consumers should be empowered with comprehensive information on the content of food. Nestle, for example, promotes the removal of over 40,000 tonnes of sugar since 2014 as part of its *Healthier Kids* [41] programme – but it is unclear whether the sugar removed was replaced with a healthy alternative, or with another sweetener, which might be equally as detrimental to healthy diets as sugar. To bolster efforts presented in the F2F strategy and empower consumers, transparency is needed regarding guidelines on healthy diets, which should be driven by public research and should go beyond the notion of reduced sugar, fat, and salt to consider access to diverse, nutrient-rich foods.

F2F emphasises the challenges relating to ultra-processed foods (accounting for 25% of all food purchased in the EU) which contribute significantly to the increasing number of overweight and obese citizens in Europe [42]. However, this is a missed opportunity to consider the food processing system in its entirety. The HLPE report states that sustainable food systems should support the supply of diverse, and *minimally processed* staple foods.

https://doi.org/10.32933/ActaInnovations.36.2• ISSN 2300-5599 • © 2020 RIC Pro-Akademia – CC BY

Beyond foods categorised as 'ultra-processed', current processing mechanisms to improve shelf life or make food items more appealing to customers can reduce their nutritional value by the time they reach the 'fork'. Yet, these are not categorised as 'ultra-processed'. For example, refined olive oil involves heavy-duty processing and strips the oil of many, if not most, of its valuable nutrients. It involves mechanical cooking and cleaning (average temperatures of 120 degrees Celsius), degumming (carried out at 60 degrees Celsius), refinement, bleaching (alters fatty acids), deodorising (temperatures of between 240 – 270 degrees Celsius), additives, 'winterisation' (cooled and filtered one more time), and hydrogenation. By the time, the oil has gone through this refinement process, it can lose substantial amounts of micronutrients [43]. Thus, rather than solely aiming to reduce the negative impact of obesogenic foods such as ultra-processed ones, a more ambitious strategy might have considered reviewing the processing of food to favour the maintenance of existing nutrients in food items.

Conclusions

The F2F strategy articulates an inspiring starting point for a coherent, harmonised and sustainable food system across the EU. The F2F strategy and its interconnected policies, offer an exciting opportunity to transform the European economic, social and environmental landscapes. EU member states could see an increase in organic land, biodiversity and a reduction of fraudulent activities and greenwashing relating to the food on the shelves. Farmers could see higher returns and improved bargaining power, and new business opportunities such as in bioeconomy or plant protein sectors could arise. Policies will have to adapt to achieve the goals in the F2F strategy. They will need to consider context-specific nature of each initiative, as well as duties towards future generations. Given the complex nature of the food system, interdependencies between sectors (e.g. health and agriculture) and across borders need to be addressed in policy and decision-making processes.

Whilst the F2F strategy aims for a system that promotes healthier and sustainable diets, it falls short in terms of aiming for a sustainable and efficient food system (as defined above), and in creating the links necessary for coherence, particularly between agriculture and nutrition. The F2F's overemphasis on the consumption sphere of the food system means the links between agriculture and nutritional outcomes have been missed, undermining the potential for the long-term shift in agricultural paradigms which are needed to achieve sustainable food systems. This overemphasis also risks disproportionately placing the burden of change on the consumer, rather than distributing it evenly across society. Further, the strategy's targets largely remain within the framework of the current food system, which aims for more and cheaper food, rather than suggesting structural changes such as short food supply chains, or reviewing concepts of food system efficiency. In the same vein, the strategy does not go far enough in its ambitions for sustainable agriculture, which should happen in harmony with local ecosystems, producing more nutrient-rich and flavourful food that promotes biodiversity growth in the region rather than depletes it. Finally, within the strategy, nature remains as an asset to be exploited, rather than an integral part of the ecosystem upon which we depend.

Further, the strategy promises to empower consumers with more readily available, transparent, and harmonised information on factors relating to environmental, nutrition and perhaps even animal welfare. Despite this, transparency was missing in the strategy on the research and guidelines that will guide these decisions. In addition, the objectives do not adequately provide citizens with the information required to make decisions on '*what foods are produced, how it's produced, processed, and distributed'*, thus weakening efforts to ensure agency across food systems. Further, the strategy makes no commitment to ensuring prioritisation nor transparency of research for nutritional guidelines, and green procurement guidelines are narrowly focussed on environmental impacts rather than nutritional ones.

Finally, the implementation of the European Green Deal would benefit from research into transboundary natural resource management, which is absent from the F2F strategy. In light of growing demands on natural resources and the shared resources across EU member states' borders, policy and legislative changes relating to a just transition should integrate provisions for transboundary challenges and opportunities.

Conflict of interest

There are no conflicts to declare

Acknowledgments

The author is grateful to Sheila Mowlds for sharing her nutrition expertise and to Colm Duffy for his insightful comments relating to agricultural systems.

Reference

[1] European Commission. Farm to Fork Strategy: For a fair, healthy and environmentally-friendly food system. May 2020. [Online]. Available: https://ec.europa.eu/food/farm2fork_en#:~:text=The%20Farm%20to%20Fork%20Strategy%20is%20at%20the%20heart%20of,%2C%20healthy%20and%20environmentally%2Dfriendly.&text=The%20Farm%20to%20Fork%20Strategy%20aims%20to%20accelerate%20our%20transition,neutral%20or. [Accessed 20 May 2020].
[2] European Commission. A European Green Deal. December 2019. [Online]. Available: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en. [Accessed May 2020].
[3] European Commission. Circular Economy Action Plan: For a cleaner and more competitive Europe. March 2020. [Online].
[4] European Commission. Biodiversity Strategy 2030. May 2020. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1590574123338&uri=CELEX:52020DC0380.
[5] Food and Agricultural Organisation (FAO). Sustainable food systems: Concept and framework. 2018. [Online]. Available: http://www.fao.org/3/ca2079en/CA2079EN.pdf. [Accessed June 2020].
[6] High Level Panel of Experts (HLPE). Food security and nutrition: building a global narrative towards 2030, Committee on World Food Security, Rome, 2020.
[7] Vatn A. An institutional analysis of methods for environmental appraisal. Ecological Economics 68 (2009), 2207–2215.
[8] Action Aid. Principles of a Just Transition for Agriculture. December 2019. [Online]. Available: https://actionaid.org/sites/default/files/publications/Principles%20for%20a%20just%20transition%20in%20agriculture_0.pdf. [Accessed June 2020].
[9] International Institute for Environment and Development (IIED). The value of valuing ecosystem services. 2012. [Online]. Available: https://www.iied.org/value-valuing-ecosystem-services . [Accessed March 2017].
[10] Bell K. Can the Capitalist Economic System Deliver Environmental Justice?. IOP Science 10 (2015), 125017.
[11] World Bank. World Development Report 2008. Washington, D.C., 2008.
[12] Hawkes C. Policy coherence across the food system for nutrition: from challenge to opportunity? 2017. [Online]. Available: https://ecdpm.org/great-insights/sustainable-food-systems/policy-coherence-across-food-system-nutrition-challenge-opportunity/. [Accessed May 2020]
[13] Benton T, Bailey R. The paradox of productivity: agricultural productivity promotes food system inefficiency. Global Sustainability, 2 (2019), 1-8.
[14] European Commission. What is Horizon 2020? [Online]. Available: https://ec.europa.eu/programmes/horizon2020/en/what-horizon-2020. [Accessed May 2020].
[15] European Commission. Horizon 2020 in Full Swing, Three Years On - Key facts and figures 2014-2016. 2018. [Online]. Available: https://ec.europa.eu/programmes/horizon2020/sites/horizon2020/files/h2020_threeyearson_a4_horizontal_2018_web.pdf. [Accessed May 2020].
[16] European Commission. Horizon Europe - Investing to shape our future. August 2019. [Online]. Available: https://ec.europa.eu/info/files/horizon-europe-investing-shape-our-future_en. [Accessed July 2020].
[17] European Commission. Fact sheet: EU Delivering on the UN 2030 Agenda. [Online]. Available: https://ec.europa.eu/info/sites/info/files/factsheet-eu-delivering-2030-agenda-sustainable-development_en.pdf. [Accessed May 2020].
[18] European Commission. Fact Sheet - From Farm to Fork: Our food, our health, our planet, our future, 20 May 2020. [Online]. Available: https://ec.europa.eu/commission/presscorner/detail/en/fs_20_908. [Accessed May 2020].
[19] European Commission. Fact Sheet – EU Green Deal: Benefits for Farmers. 20 May 2020. [Online]. Available: https://ec.europa.eu/commission/presscorner/detail/en/fs_20_909. [Accessed May 2020].
[20] European Commission. Fact Sheet – Economic Impacts of Biodiversity. 20 May 2020. [Online]. Available: https://ec.europa.eu/commission/presscorner/detail/en/fs_20_907. [Accessed May 2020].
[21] Wageningen University. Circularity in Agricultural Production. 2018. [Online]. Available: https://www.wur.nl/upload_mm/7/5/5/14119893-7258-45e6-b4d0-e514a8b6316a_Circularity-in-agricultural-production-20122018.pdf. [Accessed June 2020].
[22] Boyd D. The Rights of Nature: A Legal Revolution that Could Save the World, Legato, U.S. dist.; Jaguar, Canadian dist., ISBN 978-1-77041-239-2, 2017.
[23] Barber D. The third plate: field notes on the future of food, New York: The Penguin Press., 2014.

[24] Fusions, Estimates of European Food Waste Levels, 2016. [Online]. Available: http://www.eu-fusions.org/phocadownload/Publications/Estimates%20of%20European%20food%20waste%20levels.pdf. [Accessed June 2020].
[25] World Wildlife Fund (WWF). Living Planet Report 2016: Risk and resilience in a new era. World Wildlife Fund International, Gland, Switzerland, 2016.
[26] Cano Pecharroman L. Rights of Nature: Rivers That Can Stand in Court. Resources, 7 (2018), 13.
[27] Food and Agricultural Organisation (FAO). Healthy Soils are the Basis for Healthy Food Production. 2015. [Online]. Available: http://www.fao.org/3/a-i4405e.pdf . [Accessed May 2020].
[28] Davis M, Abhold K, Mederake L Knoblauch D. Nature-based solutions in European and national policy frameworks, 2018. [Online]. Available: https://www.ecologic.eu/15856. [Accessed June 2020].
[29] European Commission. Nature-Based Solutions. [Online]. Available: https://ec.europa.eu/research/environment/index.cfm?pg=nbs. [Accessed May 2020].
[30] Rosenstock T, Dawson IK, Aynekulu E, Chomba S, Degrande A, Fornace K, Jamnadass R, Kimaro A, Kindt R, Lamanna C, Malesu M, Mausch K, McMullin S, Murage P, Namoi N, Njenga M, Nyoka I, Valencia AMP, Sola P, Shephard K, Steward P. A Planetary Health Perspective on Agroforestry in Sub-Saharan Africa One Earth 1 (2019), 330-344.
[31] Nesshover C, Assmuth T, Irvine KN, Rusch GM, Waylen KA, Delbaere B, Haase D, Jones-Walters L, Keune H, Kovacs E, Krauze K, Kulvik M, Rey F, van Dijk J, Vistad OI, Wilkinson ME, Wittmer H. The science, policy and practice of nature-based solutions: An interdisciplinary perspective. Science of the Total Environment 579 (2017), 1215-1227.
[32] Bahadur K, Dias GM, Veeramani A, Swanton CJ, Fraser D, Steinke D, Lee E, Wittman H, Farber JM, Dunfield K, McCann K, Anand M, Campbell M, Rooney N, Raine NE, Van Acker R, Hannger R, Pascoal S. When too much isn't enough: Does current food production meet global nutritional needs? PLoS ONE 13 (2018), e0205683.
[33] Food and Agricultural Organisation (FAO). State of Food and Agriculture 2013: Food systems for better nutrition. 2013. [Online]. Available: http://www.fao.org/publications/sofa/ 2013/en/. [Accessed June 2020].
[34] Martinez S, Hand M, Da Pra M, Pollack S, Ralston K, Smith T, Vogel S, Shellye C, Lohr L, Low S, Newman C. Local Food Systems: Concepts, Impacts, and Issues. Economic Research Service Number 97, May 2010.
[35] Augere-Granier M. Short food supply chains and local food systems in the EU. European Parliament Research Service, PE 586.650, September 2016.
[36] European Commission. Environment - what is GPP? 2015. [Online]. Available: https://ec.europa.eu/environment/gpp/faq_en.htm. [Accessed May 2020].
[37] Cioci G, Olivan PH, Pinzauti I. Fresh, Healthy, and Sustainable Food: Best Practices in European Healthcare, Health Care Without Harm. December 2016. [Online]. Available: https://noharm-europe.org/sites/default/files/documents-files/4680/HCWHEurope_Food_Report_Dec2016.pdf. [Accessed May 2020].
[38] Harvard School of Public Health. The Nutrition Source: Nutrition and Immunity. [Online]. Available: https://www.hsph.harvard.edu/nutritionsource/nutrition-and-immunity/. [Accessed June 2020].
[39] World Health Organisation (WHO). Food and nutrition tips during self-quarantine online guide. 2020. [Online]. Available: https://www.euro.who.int/en/health-topics/health-emergencies/coronavirus-covid-19/technical-guidance/food-and-nutrition-tips-during-self-quarantine. [Accessed June 2020].
[40] European Commission. European Research & Innovation for Food & Nutrition Security. Publications Office of the European Union, Luxembourg, 2016.
[41] Nestle. Nestle for Healthier Kids. [Online]. Available: https://www.nestle.com/csv/global-initiatives/healthier-kids/home. [Accessed 2020].
[42] European Commission. Towards a sustainable food system: Moving from food as a commodity to food as more of a common good. Publications office of the EU, Luxembourg, 2018.
[43] Kock Wai Ng T, Appukutty M, Shyam S, Tee Voon P, Selvaduray KR. Cooking Oils in: Bagchi D, Nari S, Sen C. Health and Sports, Nutrition and Enhanced Sports Performance (Second Edition) Muscle Building, Endurance, and Strength. Science Direct, 2018, pp 751-756
[44] European CSA Research Group, Overview of Community Supported Agriculture in Europe 2016. [Online]. Available: https://www.accesstoland.eu/IMG/pdf/overview-of-community-supported-agriculture-in-europe-f.pdf. [Accessed June 2020].

WATER-PARAFFIN DISPERSION SYSTEMS: MANUFACTURING AND APPLICATION

Alla Yovchenko
Cherkasy State Technological University, Department of Energy Technologies
460 Shevchenko Boulevard, 18006 Cherkasy, Ukraine
https://orcid.org/0000-0002-7069-1092

Sergii Bespalko*
Cherkasy State Technological University, Department of Energy Technologies
460 Shevchenko Boulevard, 18006 Cherkasy, Ukraine, s.bespalko@chdtu.edu.ua
https://orcid.org/0000-0002-7542-5498

Oksana Tryhub
Cherkasy State Technological University, Department of Automobiles and Technology of their Operation
460 Shevchenko Boulevard, 18006 Cherkasy, Ukraine
https://orcid.org/0000-0001-7312-6921

Sviatoslav Poliakov
Cherkasy State Technological University, Department of Energy Technologies
460 Shevchenko Boulevard, 18006 Cherkasy, Ukraine

Guy Baret
Nexthorizon Sasu
12 rue de la Martellière, 38500 Voiron, France

Alberto Munoz Miranda
University of Rostock, R&D in Renewable Energy
Erich-Schlesinger Str. 20, 18059 Rostock, Germany

Abstract
The paper presents the study results of the stability and heat storage capacity of paraffin-in-water phase change suspensions (PCSs) obtained by the homogenization of paraffin and water in the developed rotary hydrodynamic homogenizer. The optimal concentration of components for obtaining stable paraffin-in-water suspensions is found. It is shown that the stable PCSs in the form of pastes, gels, and liquids can be obtained depending on the concentration of water, paraffin, and the surface-active agent (SAA) as well as its type.
In addition, the scheme of the solar heating system with the heat storage tank where the PCS functions both as the heat transfer fluid and the heat storage media is presented. It is shown that the use of PCS in the domestic solar heating system allowed the heat storage capacity of the storage tank to be increased by 25% as a result of the high fusion heat of paraffin and the high value of the water specific heat capacity. The estimation of the saving rate from applying fluid PCS as a heat storage medium is also presented and discussed.

Keywords
heat storage; phase change material; phase change suspension; surface-active agent; enthalpy; solar heating system

Abbreviations

PCM	phase change material
PCS	phase change suspension
SAA	surface-active agent
HLB	hydrophilic-lipophilic balance
LED	light emitted diode
GnP	graphene nano-platelets

https://doi.org/10.32933/ActaInnovations.36.3• ISSN 2300-5599 •

Nomenclature

Δh_w enthalpy change of water, kJ/kg
Δh_{PCMs} enthalpy change of PCM when heated from the initial temperature to the melting point, kJ/kg
Δh_{PCM} latent heat of PCM, kJ/kg
Δh_{PCMl} enthalpy change of PCM when heated from the melting point to the final temperature, kJ/kg
$\Delta h_{SAA1}, \Delta h_{SAA2}$ enthalpy change of the Tween hydrophilic surfactants and the Span hydrophobic surfactants respectively, kJ/kg
X_{PCM}, X_w, X_{SAA1}, X_{SAA2} mass concentration of PCM, water, hydrophilic surfactants Tween, hydrophobic surfactants Span, respectively, %
c_p^w isobaric specific heat of water, kJ/kg·K
c_p^{PCMs} isobaric specific heat of the PCM in a solid state, kJ/kg·K
c_p^{PCMl} isobaric specific heat of the PCM in a liquid state, kJ/kg·K
c_p^{SAA1} isobaric specific heat of Span surfactants, kJ/kg·K
c_p^{SAA2} isobaric specific heat of Tween surfactants, kJ/kg·K
t_1, t_2 initial and final temperatures respectively, °C
t_{pt} phase-transition temperature of PCM, °C
Δt difference between the initial and the final temperatures, °C.

Introduction

Mixtures of water and PCM are one of the most promising heat-storage materials for use in heating, ventilation, and air-conditioning systems. The mixtures are called phase change suspensions (PCSs) because they can change their aggregate state at operating temperatures.

Most often, paraffin consisting mainly of straight- or branched-chain hydrocarbons C_nH_{2n+2} is used as PCM [1]. The crystallization of the hydrocarbon chains releases a large amount of latent heat. For example, octacosane $C_{28}H_{58}$ when melted at +61.3 °C may store about 224.3 kJ/kg of heat. In contrast to paraffin, about 4.2 kJ of heat is required to change the temperature of 1 kg of water by 1 °C. That is to say, that a storage tank filled with paraffin heated from +61.3 °C to +63.3 °C (2 degrees only) stores as much heat as a storage tank filled with water and heated from +26 °C to +80 °C.

The melting point of PCM defines the field of the potential PCS applications. For example, tetradecane-based PCS ($C_{14}H_{30}$) with a crystallization temperature of around 8 °C is suitable for use in air-conditioning systems [1]. Hexadecane-based PCS ($C_{16}H_{34}$) with a crystallization temperature of about 20 °C is used for increasing the heat storage capacity of building materials [2, 3]. Octacosan ($C_{28}H_{58}$) with a melting point at 61.3 °C is an appropriate material for the storage of thermal energy in the domestic solar heating and hot water supply systems [4, 5].

The main tasks of the recent R&D efforts in this field were as follows:

- Estimation of the optimal weight concentration of PCM, SAA, and nanoparticles for decreasing the subcooling effect, increasing PCS heat storage capacity and heat conductivity as well as the study of the properties of the obtained PCS [4-14],
- Development of the systems for practical PCS applications [8, 15, 16],
- Determination of optimal configuration of the heat exchangers for the heat transfer enhancement [10, 17-25],
- Study of the heat transfer processes in PCS at natural and forced convections [17-23, 24-27].

Reddy K. et al. [6], studied various heat transfer methods to improve the performance of the heat storage tank in the solar heating system. It was shown that the main reason, which limits the use of PCSs, is their time instability. It was concluded that the application of PCSs, which can undergo many melting-crystallization cycles without affecting the thermophysical properties, is necessary.

The methodology for determining the thermal characteristics of the solar heating system depending on the solar radiation intensity and the operating temperature of the PCM was proposed by P. Feliński [7]. According to that study, the heat storage capacity of a tank filled with PCMs is higher by 20.5% compared to the conventional heat storage tank filled with water. It was concluded that the performance of the solar heating system can be improved by applying PCMs with different melting points and operating temperatures. Nevertheless, further research is still needed to overcome some drawbacks relevant to PCMs.

Mohamed E. Zayed et al. [8] described various schemes of thermal energy storage systems. In the study, different ways useful for the improvement of the heat transfer in PCM, heat storage efficiency, and thermodynamic optimization have been evaluated.

https://doi.org/10.32933/ActaInnovations.36.3• ISSN 2300-5599 •

In recent years, PCSs are considered not only as a heat storage material but simultaneously as a heat transfer fluid in the solar heating systems. In the research work by Chen J. and Zhang P. [9], the conditions under which PCS is still a fluid medium, and whether it can be conveyed by a regular pump were considered. According to the obtained data, PCS is a fluid with a maximum PCM concentration of up to 30 % displaying Newtonian fluid properties. The thermophysical characteristics of PCSs at such PCM concentrations were defined. It was shown that the most common problems of using PCM in the heat storage systems are subcooling, low thermal conductivity, and low heat transfer rate, which lead to an increase in the time of charging and discharging of the heat storage reservoir as well as productivity reduction.
The application of PCS as a heat storage substance has the following advantages:

- the PCS components are not toxic as well as neither flammable nor explosive in the working temperature ranges,
- possibility to be reused or recycled,
- can easily be separated from other materials,
- chemical inertness to the structural materials of a storage reservoir,
- small change in the specific volume during melting-crystallization,
- enhanced heat storage capacity because of the high fusion heat of paraffin and the high specific heat capacity of water,
- less volume and size of the reservoir needed to store the same heat amount compared to water,
- less heat losses due to the isothermality of the heat storage with PCS,
- possibility to convey PCS using a regular pump,
- in some cases, the possibility to substitute conventional heat transfer fluids for PCS undergoing the phase change,
- availability in large quantities and cost effectiveness.

Despite the above-mentioned advantages, PCS also has some drawbacks:

- relatively less stability of PCS (up to 300 proven melting-crystallization cycles at the highest temperature of about 80 °C),
- subcooling effect, i.e. state of the substance when the PCM remains a fluid medium at temperatures well below its crystallization point,
- low heat transfer rate leading to longer charging and discharging, which results in less productivity,
- necessity to apply special facilities for homogenization of water and PCM,
- necessity to add SAA to make PCSs more stable.

In the research [10-14], the use of nanoparticles of various materials with high thermal conductivity, e.g. metal oxides, metal nitrides, silicon oxide, graphite, graphene, and etc. was proposed to reduce the subcooling phenomenon. The influence of the size, type, and a number of nanoparticles on the PCS thermal conductivity and reduction of the subcooling phenomenon was also studied.
Z. Khan and Z. Ahmad Khan [10] experimentally and numerically studied the thermal conductivity and dynamic viscosity of PCS as well as the heat transfer rate, temperature distribution, velocity of the phase change, and the heat storage capacity of the system depending on the size and concentration of the nanoparticles such as aluminum oxide (Al_2O_3), aluminum nitride (AlN), grafite (Gt) and graphene nano-platelets (GnP). According to the research results obtained, all additives affect the overall heat storage capacity of the latent heat storage system and increase the dynamic viscosity of PCSs, which in turn affect natural convection. On the other hand, the effective thermal conductivity of paraffin is significantly enhanced with the additives.
Fangxian Wang et al. [11], investigated influence of graphite nanoparticles added to the fluidic PCSs on the heat transfer. It was shown that PCSs based on the 20% of PCM and 0.1 % of the graphite additive have a 20% higher heat conductivity compared to PCSs without additives. In the temperature range from 18°C to 80 °C, heat storage efficiency is 86%, which shows that PCSs have great potential for applications as the advanced heat transfer fluid in the low temperature systems with direct absorption solar collectors.
In other research work, Fangxian Wang et al. [12] studied thermal properties of PCSs in the range of the PCM and graphite mass fractions from 15 to 25 wt.% and 0.04-0.1 wt.% respectively. According to the research, results obtained PCSs based on 20 wt.% of $C_{28}H_{58}$ paraffin and 0.07 wt.% of graphite exhibits better performance. At such concentration of the components, the overall heat storage capacity of PCSs is 1.64 times higher compared to distilled water.
Zhang et al. [13], applied hydrophobic SiO_2 nanoparticles as a nucleating agent to reduce the supercooling effect.

https://doi.org/10.32933/ActaInnovations.36.3• ISSN 2300-5599 •

It was shown that the increase in the SiO_2 concentration up to 3 wt.% reduces supercooling. Nevertheless, further increase in the SiO_2 concentration up to 5 wt.%, along with the further supercooling reduction, leads to a decrease in the heat storage capacity by 20%. That is why the optimal concentration of the additive nanoparticles was found to be 3 wt.%.

Fangxian Wang et al. [14, 15], comprehensively studied PCSs with regard to their production process, thermal properties, rheological behavior, heat transfer process as well as PCS applications in the solar heating systems.

Inaba et al. [17], studied heat transfer at the natural convection in a rectangular vessel filled with PCS containing PCMs in the range of concentrations between 5-30%. The results show that the PCM concentration has a negligible effect on the Nusselt number when the PCM is in a solid state. However, during the phase change at low Rayleigh numbers and with increase in the PCM concentration, the Nusselt number rises. It is also shown that viscosity decreases the natural convection at the PCM concentration of more than 10%.

Morimoto and Kumano [18], experimentally and numerically studied the laminar forced convection in a cylindrical pipe. It was shown that the developed mathematical model agrees with the experimental results excepting PCSs based on 10% of PCM.

According to the research works [18-23], the heat transfer characteristics are enhanced at the laminar forced convection in the phase change of PCSs. It was also revealed that the Nusselt number increases with the rise in the PCM concentration, Reynolds numbers [21] and with applying a coiled double-tube heat exchanger [19, 20]. It was also found that the pressure drop due to the viscous friction grows with the increase in the PCM concentration [23].

The analysis of the turbulent forced convection revealed that its properties are similar to those at the laminar forced convection [24-27].

The issue of obtaining stable suspensions and the forces acting in the homogeneous paraffin-water mixture was considered by Sanfeld et al. [28]. As a result, a concept of the suspension stability based on the droplet deformation theory was presented.

Recently, various methods for studying the kinetic stability of PCSs have been developed. Subjecting PCSs to melting and crystallization cycles is one of them. Here, the occurring partial coalescence mechanism leads to the destruction of PCS micro volumes, and as a result, a layer of water is liberated. In this case, the PCS stability is determined by the thickness of the water layer formed as well as the time of PCS separation into two phases: the upper phase with a lower density, and the bottom phase with a higher density.

At the same time, the stability of the PCSs depends significantly on the type of the surface-active agent (SAA). Oil-soluble SAAs, characterized by a hydrophilic-lipophilic balance (HLB) lower than 10, are used to prepare so-called water-in-paraffin suspensions. On the other hand, water-soluble SAAs with an HLB higher than 10 are used to produce paraffin-in-water suspensions.

Span Surfactants are oil-soluble and have an HLB range from 1.8 to 4.7. For instance, Span-60 is a sorbitan monostearate with HLB 4.7, Span-80 is a sorbitan monooleate with an HLB of 4.3. In contrast to Span, Tween surfactants are well soluble in water and organic solvents, easy to mix with hydrocarbons and fats. Tween-60 and Tween-80 are polyethylene glycol sorbitan monooleate having an HLB of 14.9 and an HLB of 15.0 respectively.

Golemanov et al. [29] studied the influence of the carbon chain length in the surfactant molecules on the suspension stability. As a result, the dependence of the carbon chain length on the critical osmotic pressure P_{OSM}^{CR} was determined. It was shown that the use of surfactants with long carbon chains (16 or 18 carbon atoms) provides more stable suspensions with a lower degree of hypothermia due to the formation of more compact and ordered adsorption layers [29, 30]. According to the study, surfactant Tween-60 is the most suitable for producing stable PCSs.

Different types of homogenizers to produce PCSs have been developed so far. They are colloid mills, mechanical mills, Manton-Gaulin homogenizing valves, rotary emulsifiers, ultrasonic dispensers, and others. The dispersion rate, stability of the suspensions obtained, and productivity of the colloid mill depend on the gap width, the rotating speed of the rotor, and the time of mixing. The optimal gap width ranges from 0.05 to 0.1 mm. However, it was found [31] that the small gaps significantly reduce the productivity of the colloid mill. The operating principle of the homogenizing valve is based on pumping the fluid mixture through a calibrated hole at a high pressure of about 20 MPa. When passing the valve, the significant pressure drop induces cavitation, which, in turn, efficiently shatters and mixes the paraffin globules with water.

In the rotary emulsifiers, the liquid flows through the nozzles or slits under pressure. Such homogenizers have some advantages compared to the homogenizing valves. They are simpler, less metal consuming, and there is no

https://doi.org/10.32933/ActaInnovations.36.3• ISSN 2300-5599 •

rapid wearing of parts. One of the drawbacks is the significant foaming of the product during mixing. The ultrasonic dispensers are increasingly popular for mixing purposes. Their operation is based on the use of oscillations in the ultrasonic wavelength range.
Mechanical mills for the production of suspensions require significantly less energy than colloid mills or homogenizers with similar production rates. However, the suspension obtained in mechanical mills has a poor dispersion rate than obtained in other apparatuses. On the other hand, the mechanical mills consume two times less energy than colloid mills, and 4-6 times less than the ultrasonic dispersers [32].
Analysis of the technologies for the production of PCSs shows that all of them have disadvantages, such as low dispersion efficiency, low productivity, complex construction, and high-energy consumption.
Rotary hydrodynamic homogenizers are the most efficient and multi-functional among a variety of apparatuses for the homogenization of multicomponent heterogeneous liquids. In this type of homogenizer, the fluids flow through the inter-cylinder gap (annulus), where the main process of homogenization takes place. The homogenization process is influenced by the regime of the fluid flow in the inter-cylinder gap. Two dimensionless numbers characterize the fluid motion in the annulus, especially the Reynolds number of axial flow, and the Taylor number. According to [33], depending on the Reynold and Taylor numbers one of the four flow modes is possible: laminar, laminar with Taylor vortices, turbulent, and turbulent with Taylor vortices. The most efficient PCS production occurs in the turbulent regime with the Taylor vortices. In this case, there are significant shear stresses, which, in turn, are responsible for the efficient mixing of paraffin with water and stable PCS formation. However, our literature review revealed that in most cases the laboratory homogenizers such as ULTRA-TURRAX T25 were used for PCS production. That is why the aim of our R&D efforts was to develop the rotor-type hydrodynamic homogenizer with the similar technical characteristics and will be able to produce PCS in large scale.

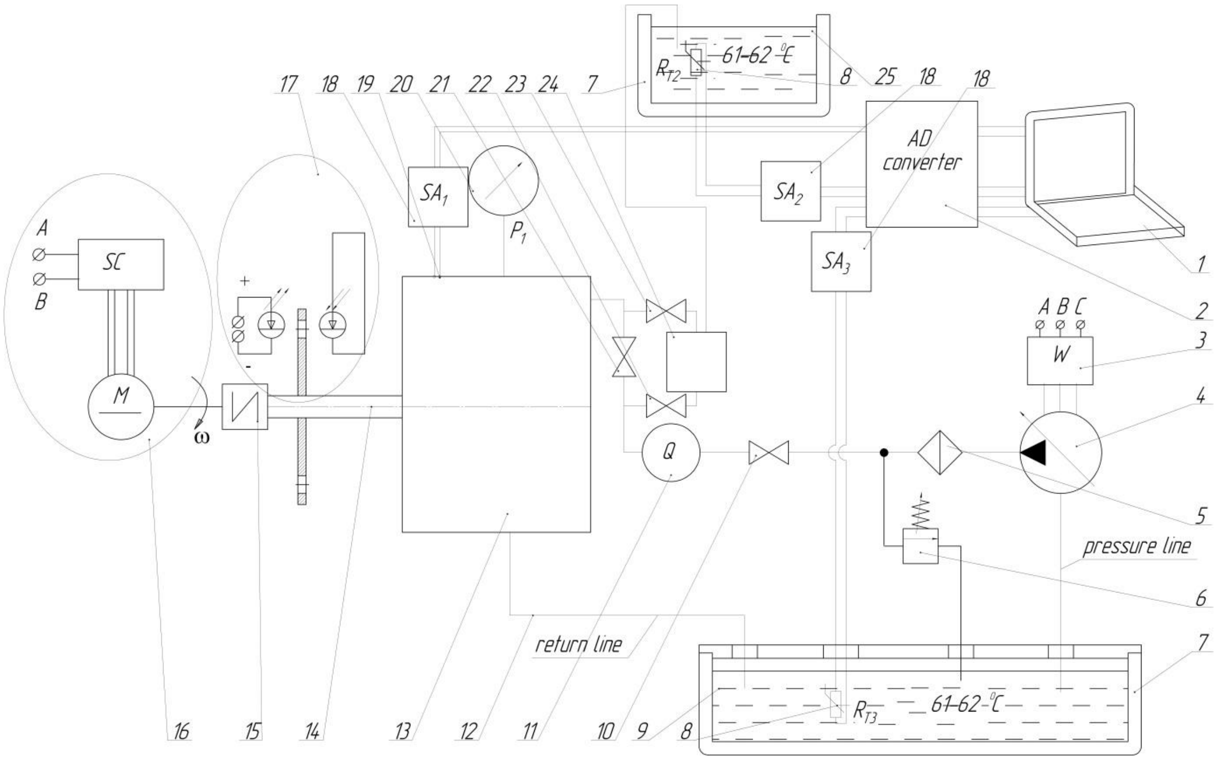
The objectives of this research were as follows:

- to check the performance of the developed rotary hydrodynamic homogenizer;
- to determine the optimal component concentrations, especially distilled water, paraffin, and surfactant, for obtaining stable paraffin-in-water mixtures;
- to determine the heat storage capacity of the PCSs obtained.

Materials and Methods

Description of the experimental setup

Paraffin and water mixing was carried out using the experimental facility (Fig. 1) equipped with a rotary hydrodynamic homogenizer, which is illustrated in Fig. 2. Non-ionic surfactants, especially Tween and Span having hydrophilic and hydrophobic properties respectively, were added to the mixture, which allowed paraffin to form stable internal media, while water continuous outer fluid.



1 - personal computer; 2 – AD converter WAD-AD12-128H; 3 - power switch; 4 - pump NXL; 5 – filter;6 - relief valve; 7 – tank; 8 - platinum temperature resistor HEL-705; 9 – "distilled water-surfactant Tween" mixture; 10, 21, 22, 23 – valves; 11 - flowmeter DDW-DS31; 12 – pipe; 13 – hydrodynamic homogenizer; 14 – rotor of the homogenizer; 15 – clutch; 16 - motor drive 3DT.31 with an adjustable-rotating speed controller (SC); 17 – device for measuring the rotational speed of the rotor; 18 - signal amplifier (SA) WAD-A-MAX; 19 - chromel-alumel micro thermocouple ∅ 0.1 mm; 20 – pressure gauge MTI-0.6; 24 – water jet ejector; 25 –"molten paraffin-surfactant Span" mixture

Fig. 1. Scheme of the experimental setup

An electrical DC motor drive 3DT.31 (16) with an elastic clutch drove the rotor of the hydrodynamic homogenizer (13). Apart from this, the electrical motor was equipped with an adjustable-rotating speed controller. In turn, the pump NXL (4) provided circulation of the working fluids, especially distilled water, paraffin, and surfactant, in the pipeline. The hydraulic system also included 0.35 m^3 tank (7), a relief valve (6), and measuring facilities.

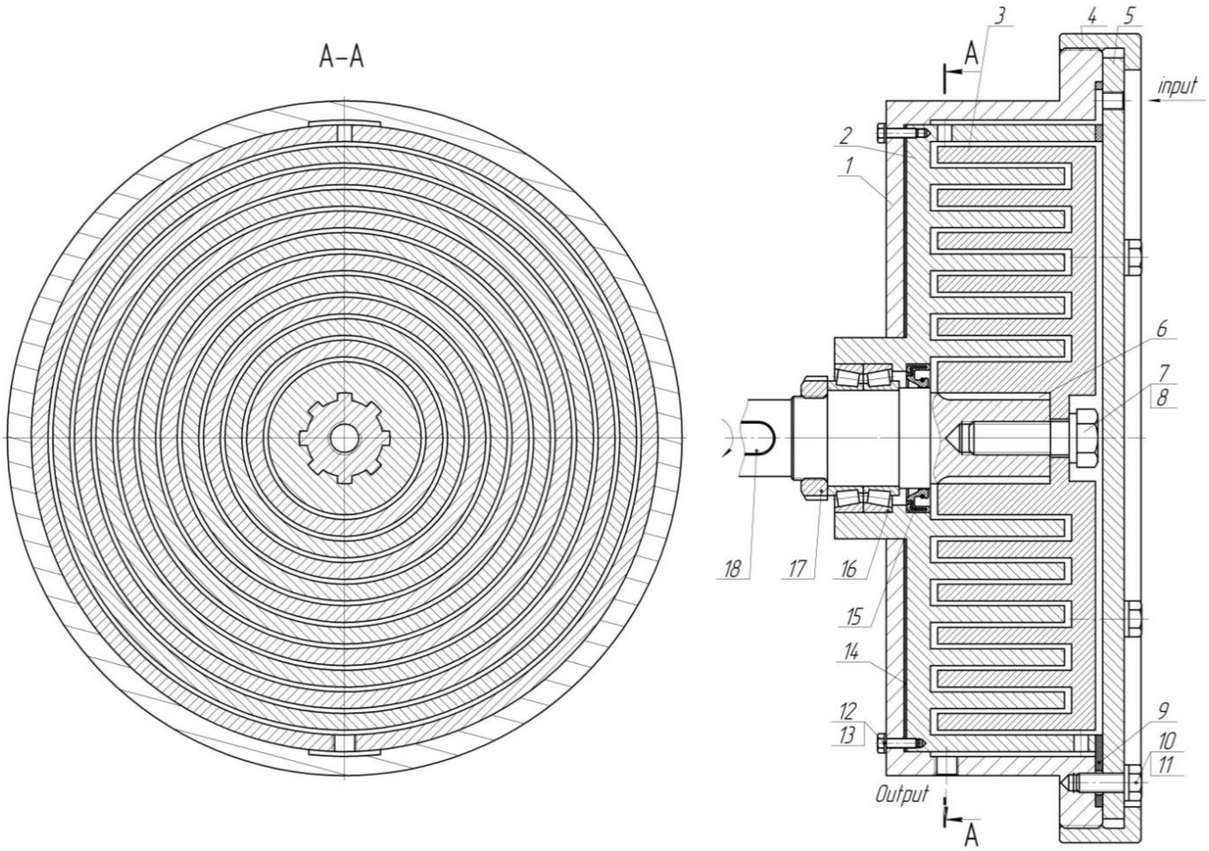
A developed device (17) measured the rotational speed of the rotor. It consisted of a LED, photocell, and rotating disk with perforated holes. The light flux, emitted by the LED, was interrupted by the baffles and the measurement system recorded the photocell signal change. The rotational speed of the rotor was determined by the frequency of the received periodic signal. The DDW-DS31 flowmeter (11) measured the volume flow rate of the working fluid in the system.

The MTI-0.6 pressure gauge (20) measured pressure within the hydrodynamic homogenizer. In the outer contour of the homogenizer, a chromel-alumel micro thermocouple with a diameter of around ∅ 0.1 mm (Fig. 2) was installed to measure the housing temperature. Platinum temperature resistors HEL-705 (8) were used to measure fluids' temperatures in the tanks (Fig.1).

WAD-A-MAX signal amplifiers (18) allowed amplification of the electrical signals generated by the temperature sensors. All signals were recorded by a WAD-AD12-128H data logger (2) with software for further analysis. The data acquisition frequency was set at 1 Hz.

In the developed hydrodynamic homogenizer, two hydraulic circuits can be distinguished (Fig. 2). The first circuit formed by the stator (2) and housing (1) creates a so-called "jacket", which envelops the mixing zone. Here, the stator (2) acts as a heat exchanger between the first and second hydraulic circuits. The second circuit forms the mixing zone where the homogenization process takes place due to the fast rotation of the rotor.

https://doi.org/10.32933/ActaInnovations.36.3• ISSN 2300-5599 •



1 – housing; 2 – stator; 3 – rotor; 4 – nut; 5 – cap; 6 – splined shaft; 7, 10, 12 – bolts; 8, 11, 13 – washers; 9, 14 – gaskets; 15 – seal; 16 – bearing; 17 - nut; 18 – keyway

Fig. 2. Hydrodynamic homogenizer

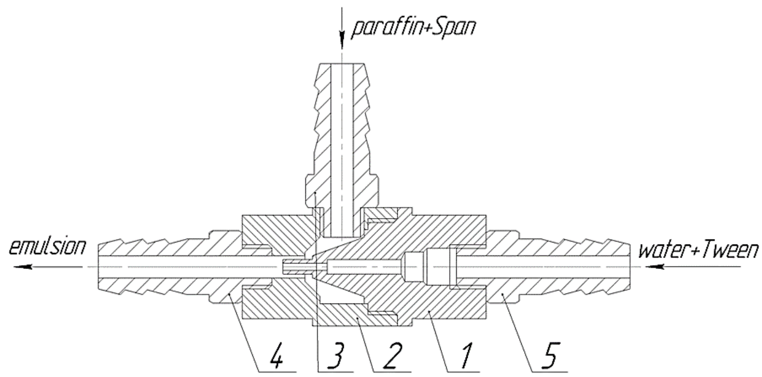
In a mixing, a significant portion of mechanical energy disappears and results in the dissipative liquid heating. Therefore, utilizing the dissipative heat by providing such an internal heat exchange between two circuits is necessary. In this case, the heat flux through the stator surface (2) is used for the preheating of the working fluid. The developed homogenizer may produce up to 1 m^3 of PCS per hour.

Method for obtaining suspensions

First, the distilled water heated in the tank (7) up to a temperature level of 61-62 °C was mixed with the Tween hydrophilic surfactant using a propeller blade mixer. At the same time, paraffin, especially octacosan$C_{28}H_{58}$, heated to the melting point was mixed with the Span hydrophobic surfactant also using a propeller blade mixer. The pump NXL (4) was applied to circulate water-Tween surfactant mixture through the hydraulic system pipeline. The fluid flow rate was controlled by the valve (10), thereby changing the pressure in the system. After filling the hydraulic system with a liquid medium, an electric DC motor (16) started to transmit torque to the rotor of the homogenizer (13). The rotation speed *n* of the homogenizer was adjusted in the range from 0 to 3000 rpm. After that, the valve (21) was closed.

The water jet ejector (24) was applied for pre-mixing the mixtures of "molten paraffin-surfactant Span" and the mixture " Tween distilled water-surfactant ". After opening the valves (22) and (23), the mixture of " Span molten paraffin-surfactant " was sucked in the mixture of " Tween distilled water-surfactant " by the water jet ejector. This mixing method allowed a more simple and even distribution of the mixture of the "molten paraffin-surfactant Span" in a mixture of the " Tween distilled water-surfactant ", which in turn enhances the main homogenization process in the hydrodynamic homogenizer.

After cooling to room temperature, the paraffin globules crystallized. The obtained homogeneous suspension was in the form of a liquid, gel, or paste, depending on the paraffin concentration. Since PCSs contains water, paraffin, and surfactant, the thermophysical properties of the PCSs are influenced by the properties of these three main components as well as their concentrations [5]. When PCSs are in the liquid form, water provides them with fluidity, while the paraffin microparticles remain in a solid state. As a result, PCSs can be conveyed by a regular pump. On the other hand, in the case of pastes, PCSs are in the form of a solid plastic mass that cannot be transported by a pump but can take any shape and fill in any cavities.



1 – nozzles; 2 - housing; 3, 4, 5 – barb fitting;
Fig. 3. Pre-mixing suspension ejector.

The procedure used to prepare a PCS is shown in Fig. 4.

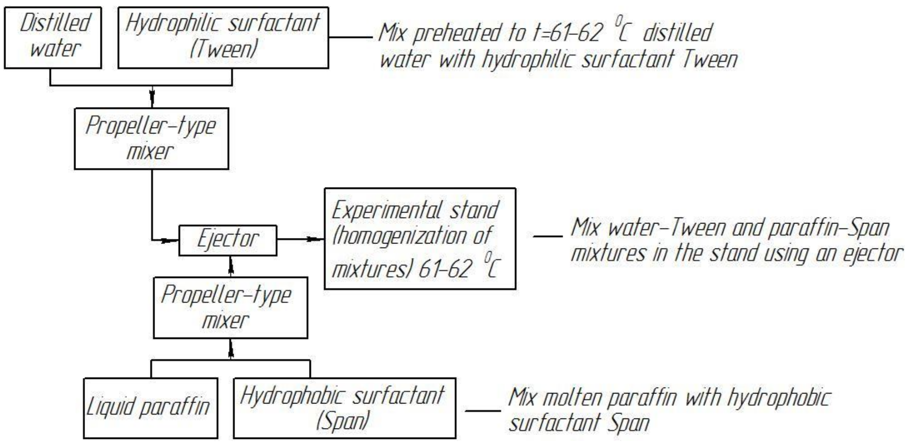


Fig. 4. The flow chart of the homogenization process used to get PCS.

<u>Method for determining the heat storage capacity</u>

The total heat storage capacity of the PCS consists of not only the heat storage capacity of paraffin but also the heat storage capacity of water and surfactants. Thus, in the temperature range from t_1 to t_2, the enthalpy change of the PCS Δh_{PCS} can be estimated using the expression as follows:

$$\Delta h_{PCS}= \Delta h_w + \Delta h_{PCMs} + \Delta h_{PCM} + \Delta h_{PCMl} + \Delta h_{SAA1} + \Delta h_{SAA2}=X_w\cdot c_p^{w}\cdot(t_2-t_1)+X_{PCM}\cdot c_p^{PCMs}\cdot(t_{pt}-t_1)+X_{PCM}\cdot\Delta h_{PCM}+ +X_{PCM}\cdot c_p^{PCMl}\cdot(t_2-t_{pt})+X_{SAA1}\cdot c_p^{SAA1}\cdot(t_2-t_1)+X_{SAA2}\cdot c_p^{SAA2}\cdot(t_2-t_1), \quad (1)$$

where Δh_w is the enthalpy change of water in the temperature range from t_1 to t_2, kJ/kg; Δh_{PCMs} is the enthalpy change of the PCM when heated from the initial temperature to the melting point [34], kJ/kg; Δh_{PCM} is the fusion heat of the PCM [34], kJ/kg; Δh_{PCMl} is the enthalpy change of the PCM when heated from the melting point to the heating temperature [34], kJ/kg; Δh_{SAA1} is the enthalpy change of Tween hydrophilic surfactants in the temperature range from t_1 to t_2 [35], kJ/kg; Δh_{SAA2} *is* the enthalpy change of Span hydrophobic surfactants in the temperature range from t_1 to t_2 [36], kJ/kg; X_{PCM}, X_w, X_{SAA1}, X_{SAA2} is the mass concentration of PCM, water, Tween hydrophilic surfactants, Span hydrophobic surfactants, respectively, %; c_p^{w} is the isobaric specific heat of water, kJ/kg·°C; c_p^{PCMs} is the isobaric specific heat of the PCM in a solid state, kJ/kg·°C; c_p^{PCMl} is the isobaric specific heat of the PCM in the liquid state, kJ/kg·°C; c_p^{SAA1} is the isobaric specific heat of Span surfactants, kJ/kg·°C [35], [36]; c_p^{SAA2} is the isobaric specific heat of Tween surfactants, kJ/kg·°C [35-37]; t_1, t_2 are initial and final temperatures respectively, °C; t_{pt} is the phase-transition temperature of the PCM, °C; Δt is the difference between the initial

and the final temperatures, ˚C.
Therefore, Eq. (1) is the correlation between the heat storage capacity of the PCS and temperature as well as the concentration of the different components.

Measuring instrument description and uncertainty analysis

- **Measuring instrument description**

Description of the tools used to measure temperature and mass of the components is presented in Table 1.

Table 1. The measuring instruments and their characteristics

Parameter	Measuring instruments	
	Reference and provider	Main characteristics
Initial and final temperature of PCS (t_1, t_2)	Platinum temperature resistors HEL-705 (Honeywell)	Range: -200÷260 °C Accuracy: Δt=±0.8%
Scales, (m)	Kenwood DS 400	Range: 0÷8 kg Accuracy: Δm=±0.25%

- **Uncertainty analysis**

The uncertainty analysis of the measured and calculated parameters was carried out based on the error propagation theory as described by Lee T.-W. [38]. Table 2 contains the total uncertainties of the measured parameters.

Table 2. Uncertainty estimation of the measured parameters

Parameter	Total uncertainty
Initial temperature (t_1)	Δt_1=±0.12 °C at 15 °C
Final temperature (t_2)	Δt_2=±0.5 °C at 62 °C
Scales, (m)	Δm=±0.25 %

Table 3. Uncertainty of the thermophysical properties of the components.

Parameter	Main characteristics
Specific enthalpy of PCM (Δh_{PCM})	Accuracy: Δh_{PCM} =±1.8 kJ/kg
Specific heat of water (c_p^w)	Accuracy: Δc_p^w=± 2 kJ/(kg ·°C)
Specific heat of PCM in solid state (c_p^{PCMs})	Accuracy: Δc_p^{PCMs}=±1.7 kJ/(kg ·°C)
Specific heat of PCM in liquid state (c_p^{PCMl})	Accuracy: Δc_p^{PCMl}=±1.92 kJ/(kg ·°C)
Specific heat of surfactants Span (c_p^{SAA1})	Accuracy: Δc_p^{SAA1}=±0.02 kJ/(kg ·°C)
Specific heat of surfactants Tween (c_p^{SAA2})	Accuracy: Δc_p^{SAA2}=±0.005 kJ/(kg ·°C)

The uncertainty of the PCS enthalpy change Δh_{PCS}^{unc} can be estimated as follows:

$$\Delta h_{PCS}^{unc}=[(\Delta h_w^{unc})^2+(\Delta h_{PCMs}^{unc})^2+(\Delta h_{PCM}^{unc})^2+(\Delta h_{PCMl}^{unc})^2+(\Delta h_{SAA1}^{unc})^2+(\Delta h_{SAA2unc})^2]^{0.5} \quad (2)$$

$$\Delta h_w^{unc}=[(\partial h_w^{unc}/\partial X_w \cdot \Delta X_w)^2+(\partial h_w^{unc}/\partial c_p^w \cdot \Delta c_w)^2+(\partial h_w^{unc}/\partial t \cdot \Delta t_{21})^2]^{0.5}\ ,\ \Delta t_{21}=(\Delta t_2^2+\Delta t_1^2)^{0.5}$$

$$\Delta h_{PCMs}^{unc}=[(\partial h_{PCMs}^{unc}/\partial X_{PCM} \cdot \Delta X_{PCM})^2+(\partial h_{PCMs}^{unc}/\partial c_p^{PCMs} \cdot \Delta c_p^{PCMs})^2+(\partial h_{PCMs}^{unc}/\partial t_{pt} \cdot \Delta t_{pt1})^2]^{0.5},\ \Delta t_{pt1}=(\Delta t_{pt}^2+\Delta t_1^2)^{0.5}$$

$$\Delta h_{PCM}^{unc}=[(\partial h_{PCM}^{unc}/\partial X_{PCM} \cdot \Delta X_{PCM})^2+(\partial h_{PCM}^{unc}/\partial h_{PCM} \cdot \Delta h_{PCM})^2]^{0.5}$$

$$\Delta h_{PCMl}^{unc}=[(\partial h_{PCMl}^{unc}/\partial X_{PCM} \cdot \Delta X_{PCM})^2+(\partial h_{PCMl}^{unc}/\partial c_p^{PCMl} \cdot \Delta c_{PCMl})^2+(\partial h_{PCMl}^{unc}/\partial t_{pt} \cdot \Delta t_{2pt})^2]^{0.5},\ \Delta t_{2pt}=(\Delta t_2^2+\Delta t_{pt}^2)^{0.5}$$

$$\Delta h_{SAA1}^{unc}=[(\partial h_{SAA1}^{unc}/\partial X_{SAA1} \cdot \Delta X_{SAA1})^2+(\partial h_{SAA1}^{unc}/\partial c_p^{SAA1} \cdot \Delta c_p^{SAA1})^2+(\partial h_{SAA1}^{unc}/\partial t_2 \cdot \Delta t_{21})^2]^{0.5}$$

$$\Delta h_{SAA2}^{unc}=[(\partial h_{SAA2}^{unc}/\partial X_{SAA2} \cdot \Delta X_{SAA2})^2+(\partial h_{SAA2}^{unc}/\partial c_p^{SAA2} \cdot \Delta c_p^{SAA2})^2+(\partial h_{SAA2}^{unc}/\partial t_2 \cdot \Delta t_{21})^2]^{0.5}$$

Table 4 presents the total uncertainties of the calculated parameters.

Table 4. Uncertainty estimation of the calculated parameters

Parameter	Total uncertainty
Uncertainty of water enthalpy change	Δh_w^{unc}=±2.88 kJ/kg
Uncertainty of the enthalpy change of the PCM when heated from the initial temperature to the melting point	Δh_{PCMs}^{unc}=±0.95 kJ/kg
Uncertainty of the enthalpy change (specific heat) of the PCM	Δh_{PCM}^{unc}=±2.13 kJ/kg
Uncertainty of the enthalpy change of the PCM when heated from the melting point to the heating temperature	Δh_{PCMl}^{unc}=±0.42 kJ/kg
Uncertainty of the enthalpy change of Tween hydrophilic surfactants	Δh_{SAA1}^{unc}=±1.42 kJ/kg
Uncertainty of the enthalpy change of Span hydrophobic surfactants	Δh_{SAA2}^{unc}=±0.28 kJ/kg
Total uncertainty of the PCS enthalpy change	$\boldsymbol{\Delta h_{PCS}^{unc}}$=±4 kJ/kg

Thus, the total uncertainty of the PCS enthalpy change (heat storage capacity) is ± 1.6 %.

Results and discussion

Pastes, gels, or liquids with predetermined properties valuable for enhancing the performance of the heat storage system can be obtained by varying the concentration of the main components in homogenization. Those properties include: the total PCS heat storage capacity, viscosity, density, and thermal conductivity.

For practical use, PCSs must be stable during the long-term period. According to the literature analysis, in our experimental study the Tween 60, Tween 80, Span 60, and Span 80 surfactants were selected for the purpose to obtain stable paraffin-in-water suspensions.

To obtain stable PCSs, the use of surfactants with hydrophilic and hydrophobic properties simultaneously is necessary. Using only one surfactant, e.g. Tween 60, made PCS unstable regardless of the PCM and distilled water concentrations (Table 5, no. 2-5, no. 11-14, no. 22-24). The ability of surfactants to stabilize paraffin-in-water suspensions for a long time is determined by a hydrophilic functional group, such as Tween 60, and a moderately developed hydrophobic part of the diphilic molecule – Span 80 (Table 5). For the first group, the hydrocarbon part of the surfactant molecule is placed in a paraffin globule and hydrophilic in water. In such a way, it protects the dispersed phase particles from coalescence and, accordingly, prevents the subsequent increase in the size of the globules. The most stable suspensions were formed by applying the surfactants with an HLB higher than 12. Increasing surfactant concentration and reducing surface tension affects the suspension stability, droplet size, and viscosity. Thus, the maximum surfactant concentration should not exceed 10 %. If the SAA concentration is higher, excess surfactant goes into the aqueous phase, which leads to an increase in the viscosity of the PCS. In this case, the PCS becomes foamy (Table 5, no. 10, no. 21), which adversely affects the stability of the suspension. The most stable PCSs were obtained at 5 % of the surfactant concentration.

Thus, the performed experiment showed that:

(1) The required PCM concentration must be greater than 45 % to obtain stable homogeneous mixtures in the form of pastes, 30-45 % to obtain stable gel-like homogeneous mixtures, and no more than 30% to obtain stable liquid homogeneous mixtures;

(2) The maximum PCM concentration must be 25 % for PCS to be a Newtonian fluid.

https://doi.org/10.32933/ActaInnovations.36.3• ISSN 2300-5599 •

Table 5. Results of the experimental study

No.	Paraffin, %	Water, %	SAA, %				PCS stability
			Tween 60	Tween 80	Span 60	Span 80	
PASTES							
1	50	40	-	5	5	-	+
2	45	45	10	-	-	-	-
3	45	45	-	10	-	-	-
4	45	45	-	-	10	-	-
5	45	45	-	-	-	10	-
6	45	45	5	-	5	-	+
7	45	45	5	-	-	5	++
8	45	45	-	5	5	-	+
9	45	45	-	5	-	5	+
10	40	40	-	10	10	-	+
GELS							
11	35.0	60.0	5	-	-	-	-
12	35.0	60.0	-	5	-	-	-
13	35.0	60.0	-	-	5	-	-
14	35.0	60.0	-	-	-	5	-
15	30.0	60.0	-	10	-	-	+
16	30.0	60.0	-	-	10	-	-
17	30.0	60.0	-	5	-	5	+
18	30.0	60.0	-	5	5	-	+
19	30.0	60.0	5	-	-	5	++
20	30.0	60.0	5	-	5	-	+
21	25.0	55.0	-	10	10	-	+
LIQUID PCSs							
22	25.0	70.0	5	-	-	-	-
23	25.0	70.0	-	5	-	-	-
24	25.0	70.0	-	-	5	-	-
25	25.0	70.0	2.5	-	-	2.5	++
26	20.0	75.0	2.5	-	2.5	-	+
27	20.0	75.0	-	2.5	2.5	-	+
28	20.0	75.0	2.5	-	-	2.5	++
29	20.0	75.0	-	2.5	-	2.5	+
30	15.0	80.0	2.5	-	-	2.5	++
31	15.0	80.0	2.5	-	2.5	-	+
32	15.0	80.0	-	2.5	2.5	-	+
33	15.0	80.0	-	2.5	-	2.5	+

«-» - PCS is not stable, «+» - PCS is stable, «++» - the most stable PCSs.

The PCSs stability was checked by the height of the water layer formed after five PCS melting-crystallization cycles. Thus, the PCSs were subjected to the five melting-crystallization cycles, and then tested which of the PCSs formed had the highest water layer, indicating the unstable PCS by itself (Table 5). In pasty suspensions, a water layer formed after ten days of observation at the bottom of the test tube. In gel-like PCSs, this happened after five days of observation. Later, this process proceeded more slowly and the suspension became stable, which was observed for 6 months.

PCSs can be considered stable when there is no increase in the droplet size, or no phase separation, and PCS retains the heat storage capacity in the planned operating conditions during the storage period. The most stable PCSs were obtained by adding Tween 60 and Span 80 surfactants simultaneously. Subsequently, PCSs based on Tween 60 and Span 80 surfactants were selected for the mathematical calculation of heat storage capacity.

The photos of the samples obtained are shown in Fig. 5.

a) b) c)

a) pasty PCS (45 % paraffin, 45 % water, 10 % SAA (Tween 60:Span 80, 1:1));
b) gel-like PCS (25 % paraffin, 65 % water and 10 % SAA (Tween 60:Span 80, 1:1));
c) liquid PCS (25 % paraffin, 70 % water and 5 % SAA (Tween 60:Span 80, 1:1))
Fig. 5. Photos of PCSs "paraffin in water" after 6 months of storage.

The experimental results obtained with regard to the PCS stability correlate well with the results presented in other research papers, especially [9, 11]. In other words, the stable PCSs obtained did not change their stability during the first 300 melting-crystallization cycles.
According to the data obtained, the PCS enthalpy change was calculated in MathCad 15 as a function of the PCM concentration, and the temperature difference between the final and initial states. The graphical representation of the received results is presented in Fig. 6.

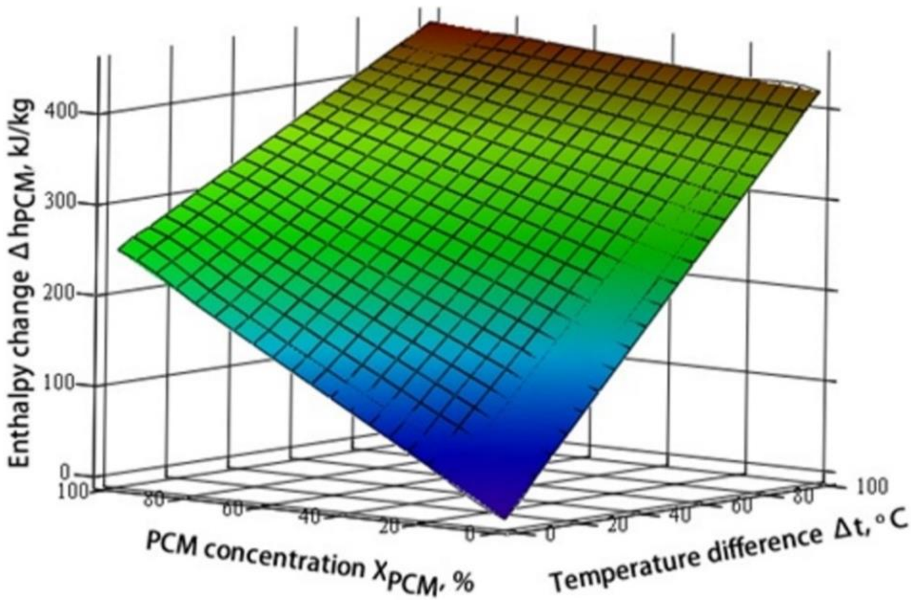


Fig. 6. 3D curve surface of the PCS heat storage capacity as a function of the PCM concentration, and the temperature difference between final and initial states

A regression equation with the regression coefficients was determined using the least-squares method. As can be seen, the regression equation obtained is described by a second-order polynomial function, which is given below:

$$\Delta h=-0.022\cdot\Delta t\cdot X_{PCM}+4.196\cdot\Delta t+2.5\cdot X_{PCM}. \quad (3)$$

According to this equation, the heat storage capacity of water as a storage media is just 168 kJ/kg at 38 °C temperature difference, whereas the PCS as a heat storage media has a heat storage capacity of about 208.3 kJ/kg at the same temperature difference. That is to say that the heat storage capacity of the PCS is higher by 24 % than that for water (see Fig. 7).

As the temperature difference in the storage tank increases, the difference between the heat storage capacity of water and the PCS decreases. However, most often the temperature difference in the storage tank is in the range of 60 °C.

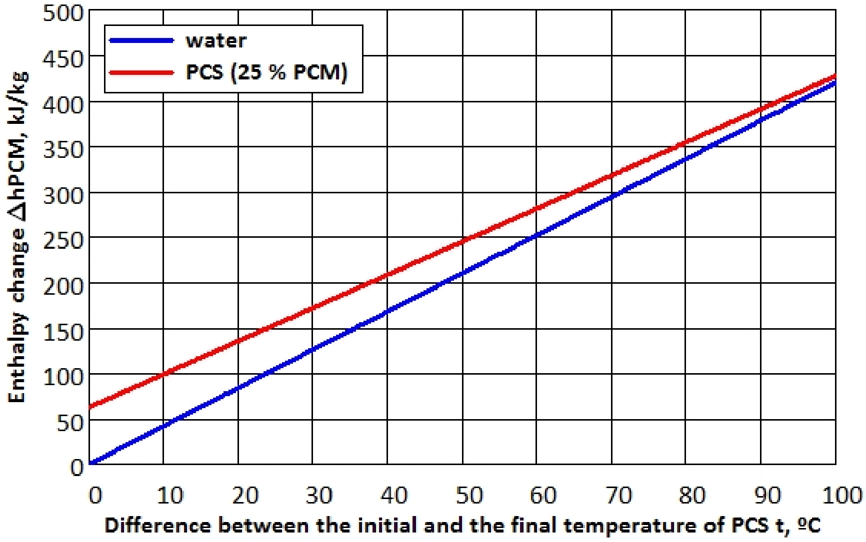


Fig. 7. Heat storage capacity Δh for water and PCS as a function of the temperature difference Δt.

<u>An embodiment of a solar heat system with PCS used as a heat transfer fluid</u>
PCSs show great potential in solar heating systems as new heat storage media as well as a heat transfer fluid. The scheme of a solar heating system where PCSs are applied as a heat transfer fluid is presented in Fig. 8.

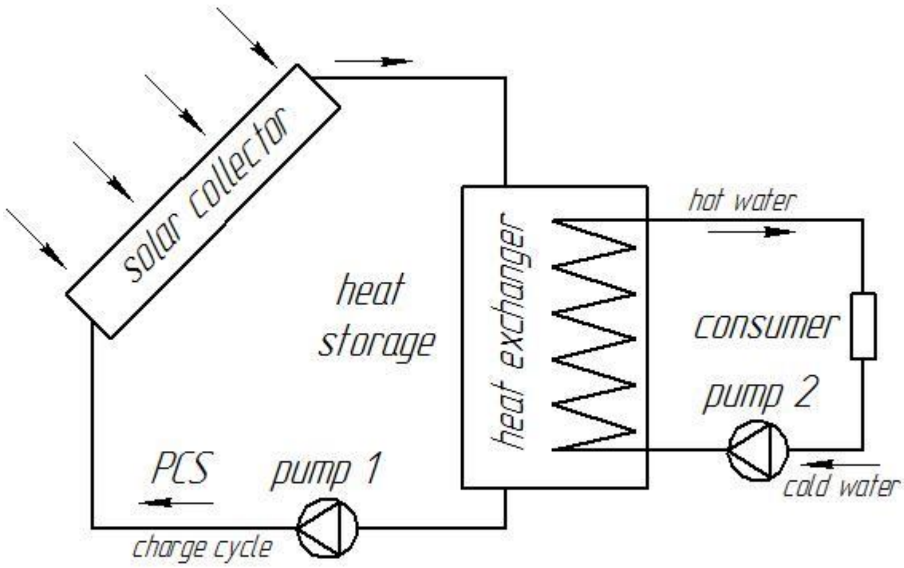


Fig. 8. Scheme of a solar heat system with PCS applied as a heat transfer fluid

In the system, the PCS is conveyed by a pump to the flat-plate collector, where it absorbs solar heat in the daytime heating up on its way to a storage reservoir. In the storage container, a coiled heat exchanger transfers the heat stored to the consumer. The system has improved heat storage capacity due to the use of the latent heat of paraffin and the high specific heat capacity of water. Thus, by applying PCSs it is possible to increase the total heat storage capacity by 24% compared to water.
PCSs with a high heat storage capacity and low energy consumption for pumping have great potential as a new heat storage media and heat transfer fluid for solar heating systems.
The estimation of the saving rate from applying PCSs as a heat storage medium compared to water in the solar heating system is presented in Table 6.

Table 6. Estimation of the saving rate

Parameters	PCS	Water
Operating period	300 melting-crystallization cycles	300 days
Initial temperature, °C	20	
Final temperature, °C	45	
Mass of the heat storage medium, kg	300	
Amount of the heat stored in one charging, kJ	46,200	31,500
Surplus of the heat stored for one charging (compared to water as a storage medium), kJ	14,700	0
Cost of the heat, Euro/GJ**	20	
Saving rate per one charging-discharging cycle, Euro/cycle	0.294	0
Saving rate per operating period, Euro	88.20	0
Cost of the PCS components, Euro***	80.26	-
Overall saving rate per first operating period, Euro	**7.94**	**0**
Overall saving rate per second operating period, Euro	**88.2**	**0**

* The saving rate was estimated regardless of the cost of homogenization process
** Cost of the thermal energy was taken from [39]
*** Data for cost of the PCS components were extracted from [40-43]

From Table 6 it can be seen that the overall saving rate per first operating period is only EUR 7.94 . Nevertheless, at the end of the first operating period (300 melting-crystallization cycles), the PCS components can be homogenized again for the purpose to be reused as the heat storage medium in next operating period lasted 300 melting-crystallization cycles as well. In this case, the overall saving rate per second operating period will constitute EUR 88.2 because the PCS components are reused.

Impact

One of the ways to decrease human impact on the environment is the use of renewable energy sources. Solar heat is likely to become the ultimate heat source in the future. However, the intermittency challenge of the solar heat generated by solar collectors must be overcome. Heat storage is one of the solutions for this intermittency challenge. That is why an increase in the efficiency and the heat storage capacity of the store is a vital problem. Currently, the most widely used systems are those where the heat storage media and the heat transfer fluid is water. Nevertheless, as shown in this study PCSs display higher heat storage capacity than water.
If PCSs are used as heat-storage media, the storage system will have the following advantages over the traditional system:

- improved heat storage capacity due to the simultaneous use of the fusion heat of paraffin and high specific heat of water;
- small thermal losses due to the isothermal accumulation process;
- the ability to transport PCSs formed by a pump;
- in some cases, it is possible to substitute for a conventional heat transfer fluid with PCSs.

This study will help to choose a correct surfactant for obtaining a stable PCS in the form of liquid, gel, or paste. The proposed PCS will help to improve the energy efficiency of the heat store as well as to increase the share of solar heat utilization. In turn, this will reduce greenhouse gas (CO_2) emissions into the environment, which is a global challenge. Thus, the study has a great impact not only from a technical but also environmental point of view.
The impact of this research will be not only on science but also on the economy because energy companies are interested in increasing the capacity of the heat storage systems operating in tandem with the solar heating systems. This will allow for the share of the solar heat utilized to increase and will result in the reduction of CO_2 emission. The study has shown that the use of PCSs as a heat transfer fluid in solar heating systems increases the heat storage capacity by 24%. This has a significant economic and environmental effect compared to traditional heat stores filled with water.

Conclusions

Based on the results obtained here, the following conclusions can be drawn:

1. The rotor-type hydrodynamic homogenizer has been developed with the productivity rate of about 1 m^3 of PCS, which is suitable for commercial application. The corresponding patent application for the homogenizer has been filed.
2. The optimal concentrations of the components, especially distilled water, paraffin, and surfactants, to obtain stable paraffin-in-water mixtures were determined. The required concentration of PCMs to obtain stable pasty mixtures should be greater than 45%, for gel-like 30-45%, for fluid not more than 30%. The most stable suspensions were formed when using a surfactant with a hydrophilic-lipophilic balance of at least 12. The maximum surfactant concentration should not exceed 5%. At higher concentrations, PCSs becomes foamy.
3. The capacity of the heat storage system increased by 24% when PCSs are applied as a heat storage medium compared to the conventional heat store based on water at the temperature difference of 25 °C.
4. PCSs have great potential as new heat transfer fluid and heat storage medium in solar heating systems. Estimation of the economics of the PCS application in the solar heating system has shown that in the first operating period the overall saving rate is only EUR 7.94 , while in each further it constitutes EUR 88.2. This fact shows that use of PCS is attractive from the economic point of view.

Conflict of interest

There are no conflicts to declare.

Acknowledgments

This research has not been supported by any external funding.

References

[1] Huang L, Pollerberg C, Doetsch C. Paraffin in Water Suspension as heat transfer and storage medium. Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT (2017), 1-8.

[2] Kalnæs SE, Jelle BP. Phase change materials and products for building applications: A state-of-the-art review and future research opportunities. Energy and Buildings 94 (2015), 150-176.

[3] Shao J, Darkwa J, Kokogiannakis G. Review of Phase change suspensions (PCMEs) and their applications in HVAC systems. Energy and Buildings 94 (2015), 200-217.

[4] Xiyao Z, Jian-Yong W, Jianlei N. PCM-in-water suspension for solar thermal applications: The effects of emulsifiers and emulsification conditions on thermal performance, stability and rheology characteristics. Solar Energy Materials & Solar Cells 147 (2016), 211–224.

[5] Yovchenko AV, Bespalko SA, Poliakov SP. Obtaining heat storage suspensions that change their aggregate state. Energy management: Status and prospects of development. V International scientific-technical and educational-methodical conference (2018), 24-25.

[6] Reddy KS, Mudgal V, Mallick TK. Review of latent heat thermal energy storage for improved material stability and effective load management. Journal of Energy Storage 15 (2018), 205–227.

[7] Feliński P, Sekret R. Effect of PCM application inside an evacuated tube collector on the thermal performance of a domestic hot water system. Energy and Buildings 152 (2017), 558-567.

[8] Mohamed EZ, Jun Z, Ammar HE, Farid AH, Ling M, Yanping D, Kabeel AE, Shalaby SM. Applications of cascaded phase change materials in solar water collector storage tanks: A review. Solar Energy Materials and Solar Cells 199 (2019), 24–49.

[9] Chen J, Zhang P. Preparation and characterization of nano-sized phase change suspensions as thermal energy storage and transport media. Applied Energy 190 (2017), 868-879.

[10] Khan Z, Ahmad Khan Z. Experimental and numerical investigations of nano-additives enhanced paraffin in a shell-and-tube heat exchanger: a comparative study. Applied Thermal Engineering 143 (2018), 777-790.

[11] Wang F, Liu J, Fang X, Zhang Z. Graphite nanoparticles-dispersed paraffin/water emulsion with enhanced thermal-physical property and photo-thermal performance. Solar Energy Materials and Solar Cells 147 (2016), 101–107.

[12] Wang F, Ling Z, Fang X, Zhang Z. Optimization on the photo-thermal conversion performance of graphite nanoplatelets decorated phase change material emulsions. Solar Energy Materials and Solar Cells, 186, (2018), 340-348.

[13] Zhang X, Wu J-Y, Niu J. PCM-in-water emulsion for solar thermal applications: the effects of emulsifiers and emulsification conditions on thermal performance, stability and rheology characteristics. Solar Energy Materials and Solar Cells 147 (2016), 211–224.
[14] Wang F, Fang X, Zhang Z. Preparation of phase change material emulsions with good stability and little supercooling by using a mixed polymeric emulsifier for thermal energy storage. Solar Energy Materials and Solar Cells 176 (2018), 381–390.
[15] Wang F, Lin W, Ling Z, Fang X. A comprehensive review on phase change material emulsions: Fabrication, characteristics, and heat transfer performance. Solar Energy Materials and Solar Cells 191 (2019), 218–234.
[16] Venglovsky VI. Diurnal heat storage with possible warming by built-in or external heat exchangers, Bulletin of the National University "Lviv Polytechnic": [collection of research works]: Theory and practice of construction 737 (2012), 21-25. (in Ukrainian)
[17] Inaba H, Dai C, Horibe A. Natural convection heat transfer of microemulsion phase-change-material slurry in rectangular cavities heated from below and cooled from above. International Journal of Heat Mass Transfer 46 (2003), 4427–4438.
[18] Morimoto T, Kumano H. Flow and heat transfer characteristics of phase change emulsions in a circular tube: part 1. Laminar flow. International Journal of Heat Mass Transfer 117 (2018), 887–895.
[19] Roy SK, Avanic BL. Laminar forced convection heat transfer with phase change material emulsions. International Communication in Heat and Mass Transfer 24 (1997), 653–662.
[20] Zhao Z, Wu T, Shi Y, Li L. An investigation on rheology and heat transfer characteristics for a phase change emulsion. Journal of Engineering Thermophysics 22 (2001), 589–592.
[21] Zhao Z, Shi Y, Zhang Y, Gai P. Flow and heat transfer characteristics of phase-change emulsion in a coiled double-tube heat exchanger. Journal of Engineering Thermophysics 23 (2002), 730–732.
[22] Ma F, Chen J, Zhang P. Experimental study of the hydraulic and thermal performances of nano-sized phase change emulsion in horizontal mini-tubes Energy 149 (2018), 944–953.
[23] Ho CJ, Lee C-Y, Yamada M. Experiments on laminar cooling characteristics of a phase change nanofluid flow through an iso-flux heated circular tube. International Journal of Heat and Mass Transfer 118, (2018), 1307–1315.
[24] Eunsoo C, Cho YI, Lorsch HG. Forced convection heat transfer with phase- change-material slurries: turbulent flow in a circular tube. International Journal of Heat and Mass Transfer 37 (1994), 207–215.
[25] Mikkola V, Puupponen S, Saari K, Ala-Nissila T, Seppälä A. Thermal properties and convective heat transfer of phase changing paraffin nanofluids, International Journal of Thermal Sciences 117 (2017), 163–171.
[26] Saarinen S, Puupponen S, Meriläinen A, Joneidi A, Seppälä A, Saari K, Ala-Nissila T. Turbulent heat transfer characteristics in a circular tube and thermal properties of n-decane-in-water nanoemulsion fluids and micelles-in-water fluids. International Journal of Heat and Mass Transfer 81 (2015), 246–251.
[27] Morimoto T, Kumano H. Flow and heat transfer characteristics of phase change emulsions in a circular tube: part 2. Turbulent flow. International Journal of Heat and Mass Transfer 117 (2018), 903–911.
[28] Sanfeld A, Steinchen A. Suspensions stability, from dilute to dense suspensions-role of drops deformation. Advanced Colloid Interface Science 140 (2008), 1–65.
[29] Golemanov K, Tcholakova S, Denkov ND, Gurkov T. Selection of surfactants for stable paraffin-in-water dispersions, undergoing solid−liquid transition of the dispersed particles. Langmuir 22 (2006), 3560–3569.
[30] Yovchenko AV, Bespalko SA, Poliakov SP. The use of suspensions that change their aggregate state in the heat power engineering and construction industry. Hydromechanics in engineering practice: materials of the XIV International Scientific and Technical Conference (2018), 99-104 (in Ukrainian).
[31] Levina KY. The use of water-bio-fuel suspensions to improve the operational and environmental performance of a diesel engine, PhD thesis (05.20.03), Tambov, (2015), 175 (in Russian).
[32] Abdo Khaled MA. Obtaining suspensions “water - fuel oil” and conformity of change in their properties with a change in composition, PhD thesis, Moscow (2007), 136 (in Russian).
[33] Ravelet F, Delfos R, Westerweel J. Influence of global rotation and Reynolds number on the large-scale features of a turbulent Taylor–Couette flow. Physics of Fluids 22 (2010), 055103.
[34] Pereverzev AN, Bohdanov NF, Roshchin YN. Paraffin production, Moscow, Himia (1973), 224.
[35] https://www.products.pcc.eu (accessed July 21, 2020)
[36] The HLB system: a time-saving guide to emulsifier selection. Anticipating needs. https://www.academia.edu/24755447/The_HLB_SYSTEM_a_time-saving_guide_to_emulsifier_selection_ANTICIPATING_NEEDS (accessed July 21, 2020)
[37] https://www.pharmencyclopedia.com.ua/article/891/polisorbati (accessed July 21, 2020)
[38] Lee T-W. Thermal and Flow Measurements CRC Press 2008.

[39] Persson U, Wiechers E, Moller B, Werner S. Heat Roadmap Europe: Heat distribution costs. Energy 176 (2019), 604-622.
[40] https://tariffs.ib-net.org/sites/IBNET/Map (accessed July 21, 2020)

[41] https://www.alibaba.com/product-detail/Chemical-raw-materials-Octacosane-630-02_1600071165687.html?spm=a2700.galleryofferlist.0.0.60787400BPwcf2 (accessed July 21, 2020)
[42] https://www.alibaba.com/product-detail/2019-Hot-Sale-Emulsifier-antistatic-agent_62237374123.html?spm=a2700.7724857.normalList.279.727f58f9YzYrGZ (accessed July 21, 2020)
[43] https://www.alibaba.com/product-detail/NT-ITRADE-emulsifier-CAS-No-1338_62487084478.html?spm=a2700.7724857.normalList.45.17ab6f9f60FxT1 (accessed July 21, 2020)

THE POSSIBILITY OF USING WASTE MATERIALS AS RAW MATERIALS FOR THE PRODUCTION OF GEOPOLYMERS

Beata Figiela
Institute of Material Engineering, Faculty of Material Engineering and Physics
Cracow University of Technology, Jana Pawła II 37, 31-864 Cracow, Poland, beata.figiela@pk.edu.pl
https://orcid.org/0000-0001-5493-0914

Kinga Korniejenko
Institute of Material Engineering, Faculty of Material Engineering and Physics
Cracow University of Technology, Jana Pawła II 37, 31-864 Cracow, Poland, kinga.korniejenko@pk.edu.pl
https://orcid.org/0000-0002-8265-3982

Abstract
This article shows the possibility of using industrial and mining waste for creating new eco-friendly materials – geopolymers. The main objective of the article is to analyze the possibilities of using new composite received from waste materials from mining industry in practical applications, especially in construction industry. The article presents benefits and potential threats for using wastes for production of geopolymers from gangue, waste from iron processing, waste from copper mining and processing, waste from chromium processing and so-called red mud from aluminum production. Research methods applied in the article are: critical analysis of literature sources, including comparison new material with other materials used in similar applications.

Keywords
geopolymer; mining waste; environmental protection; mine tailing

Introduction

The European Union's policy regarding the production and use of waste from all walks of life aims to reduce its impact on the environment and health. As Eurostat data shows, waste from mining and extraction of minerals is second in the European Union and represents 25.3% of waste generated by the economy [1]. According to the Polish Geological Institute in Poland, this waste constitutes about 55% [2]. The mining industry in Poland and the European Union generates a large percentage of waste that is not properly managed. Identifying new possibilities for their application is an important and current topic of research around the world. Estimates say that only 55.2% of the generated carbon combustion residues are reused, largely by the cement and mining industries, however, these solutions do not use all the waste generated, therefore there is still a need for solutions to remove carbon residues that are also friendly the environment [3].

Limiting the consumption of mineral and natural resources in the world for building materials leads to the search for alternative solutions of the main sources of raw materials. The reuse of industrial waste is just such a strategy. Research is carried out with different types of waste, among others bottom ash and marble powder, which are used in red clay mixtures for the production of ceramic materials. The addition of marble residue allowed to observe a decrease in mechanical properties and an increase in porosity. In turn, the addition of bottom ash did not affect the mechanical properties, while it improved the porous properties, compared to traditional samples [3].

Alkali-activated materials e.g. waste sludge from tungsten mining. They are used in research to replace Portland cement and potentially thermal insulation materials. They reduce CO2, emissions and thus global warming. Re-se of some mineral wastes using the alkaline activation process technology is done by mixing precursors, i.e. mineral wastes, with alkaline solutions. Research on this material as an alkali-activated binder proves that, in combination with red clay waste or polished blast furnace slag, compressive strength and critical pore size are reduced. In the second case, the tests are carried out with aluminum powder as a foaming agent [4].

Data from the United Nations Food and Agriculture Organization show that around 700 million tons of rice are harvested worldwide every year. Residues in the form of rice husk are burned to generate electricity and reduce waste [5]. Rice husk is a hard protective cover for grain, its components are: cellulose (50%), lignin (25% -30%),

https://doi.org/10.32933/ActaInnovations.36.4• ISSN 2300-5599 •

silica (15%-20%), water (10% - 15%). Combustion under controlled conditions removes cellulose and lignin and leads to the formation of ash, which consists of amorphous silica with a cell structure [6]. Rice husk ash (RHA) is used in construction as a partial replacement for cement and such use requires its specific properties. Cement substitution improves concrete strength from 1-3 days of maturing, and ensures the availability of concrete in developing countries, thanks to low ash costs [6].

The American manufacturer Goodyear Tire and Rubber Company specializing in the automotive industry, mainly in the production of tires and rubbers, is conducting tests on the production of tires from silica obtained from rice husk ash. This application provides an alternative source of silica and is environmentally friendly [7].
The term "geopolymers" was proposed by the French scientist Davidovits, who discovered that the strength of ancient concrete is due to the presence of alkaline aluminosilicates in the structure. The aluminosilicate cement has high mechanical strength [8].

Geopolymers are inorganic polymers produced at low temperatures not exceeding 100 °C [9], resulting from the synthesis of silicon and aluminum and obtained geologically from minerals. They can be produced on the basis of both natural raw materials and waste materials [10]. Metakaolin is the most commonly used material for the synthesis of geopolymers. Its main advantage is the constant and repeatable composition, while the disadvantage is that it is very expensive, which limits the development of geopolymers [11]. Slags and ashes are the second most commonly used raw material in the production of geopolymer materials. Slags are used both as a basic raw material for synthesis and as an addition to other raw materials [12]. The production of geopolymers based on rice husk ashes or palm oil [12] is less popular. These ashes come from burning products of plant origin. They are rich in silicon, but poor in aluminum, which is why they usually require the use of additives for the synthesis process [13].

Minerals used in the synthesis of geopolymers also include materials of volcanic origin, in particular volcanic tuffs. Tuffs are pyroclastic rocks that were formed by cementing various material fractions with clay or silica binder [14].

Methods

The aim of the article is to show the possibilities of using waste materials from the mining industry as structural elements made of geopolymer materials. The research method used in the article is a critical analysis of literature sources. Examples from world literature are analyzed showing the possibilities of using mining waste, in particular from the extraction of hard coal and metal ores, as well as from the processing of mineral resources as a material for the production of environmentally friendly composites.

Literature databases such as ScienceDirect, ResearchGate and Google Scholar were used for the analysis. The review was based on the search for articles based on the terms gangue, waste from the mining industry, i.e. iron ore, copper ore, chromite ore and red mud in combination with the term geopolymer.

Results and discussion

<u>Coal gangue</u>

Coal gangue is a byproduct of hard coal mining around the world. It is a material whose quantity increases rapidly with energy consumption. In China, annual coal production is over 70 million tons, which gives over 500 million tons of deposited gangue [15]. Its use is used to a small extent, namely for the production of aggregates, reclamation of degraded areas, as a component of energy mixtures for combustion processes [16]. The main components of gangue associated with coal mining are illite, quartz and kaolinite, which contain a large amount of silicon oxide and aluminum oxide. Their chemical composition makes them potentially a good raw material in the process of alkaline activation [17]. In order to improve the reactivity of gangue to be used as a cement substitute, its activation is needed due to the relatively stable chemical structure. The main activation methods: thermal, mechanical, microwave and compound activation are studied in detail for gangue interaction. It is possible to use only one of these processes for material activation, however, optimal properties are obtained by mechanical activation - milling (fine particles show higher reactivity) and thermal activation in the calcining process [17]. Noteworthy is the fact that the best material properties are characterized by gangue-based components that have a high content of amorphous aluminosilicate [18]. The next important elements are the content of aluminum and active silicon, i.e. reactive components [19].

https://doi.org/10.32933/ActaInnovations.36.4• ISSN 2300-5599 •

Research on the use of gangue for the production of geopolymers was carried out in Chinese centers on samples where it was used as an addition to blast furnace slag, slaked lime and gangue itself as the basic raw material [11]. Sodium hydroxide (NaOH) and sodium silicate (Na2SiO3) were used for the alkaline activation process [19]. The lowest strength properties were obtained by samples based on the gangue alone. Samples reached 20.19 MPa after 28 days and 2331 MPa after 60 days. These values are significantly lower than in the case of Portland cement, which strength after 28 days is about 42.5 MPa, but they are comparable with lower grade concretes [19].

Materials with the addition of blast furnace slag had higher mechanical properties than the materials from the first group [19]. The best results were obtained for 40% and 50% of the slag addition, obtaining values of 40.18 MPa after 28 days and 43.22 after 60 days for samples with 40% slag content [19]. The obtained properties are comparable to the mechanical strength of Portland cement. A third group of samples was prepared based on 60% gangue and 40% slag compositions [19]. Slaked lime was added to the mixture in these proportions as 2,5-20% by weight of the composition. In this case, the compressive strength was: 60.24 MPa after 28 days and 63.38 MPa after 60 days. These values significantly exceed the properties obtained for Portland cement and give wide possibilities of using the new material. Phases specific to structural concrete are obtained for this kind of samples, not geopolymers [19].

Researchers are also investigating the impact of gangue activation on the properties of geopolymers based on it. The macromechanical and microstructural changes of geopolymers based on gangue rock, activated by mechanical and thermal methods were examined. The effects that have been observed in the case of thermal activation show that the optimal temperature is 800 °C and then the structure of active metakaolinite is formed and the value of uniaxial compressive strength of geopolymers is the highest. At a temperature of 900°C, this structure is destroyed, which is unfavorable for geopolymerization and thus reduces compressive strength. Activation of gangue at 700 °C showed similar conclusions [20].
Research on gangue is carried out mainly in China and focuses on its use as a material for structural use [21]. Mechanical properties and durability of building materials based on gangue are important. Already a small addition as a cement substitute, in the amount of 10% -20% by weight, becomes a sustainable and ecological approach [15].

<u>Iron ore waste</u>
Research on the use of iron ore waste (IOT) for the production of geopolymer materials, among others, is carried out with pure waste and in mixtures with glass wool residues replacing 10%, 20%, 30% by mass of iron ore waste. Compression and bending strength tests were conducted after 7 days on prismatic samples. Compressive values above 100 MPa and 20 MPa bending strength were achieved [22]. Iron ore wastes require pre-treatment in several stages because they contain elements harmful to health. As a rule, this raw material in the geopolymer production process is combined with other materials, e.g. fly ash [23].
India has been among the largest raw steel producers on the world market since 2017. The large development of this country causes an increase in the steel and iron industry, which is also associated with an increase in the production of waste from this extraction. Research was conducted on the use of iron ore waste from two different mines to produce geopolymer materials [24].

The first waste material was from the Bellary mining area (BMM Ispat). The first mixture with BMM mine waste was prepared with the addition of blast furnace slag (GGBS) and slaked lime. The iron ore waste was mixed in an amount of 30-50% with blast furnace slag in an amount of 25-45%, so that the total for each composition was 75%. Lime was added in a constant amount of 5%, as was the concentration of sodium silicate solution as 20%. The resulting paste was made of 230x115x75 mm brick. It was observed that at increased iron ore content, compressive strength increased [24]. A second mix was prepared with iron ore waste, fly ash, slag sand (admixed with blast furnace slag and other aluminosilicate compounds from Jindal Steel LTD., Karnataka in India), blast furnace slag and sodium silicate solution. It has been observed that the increase in iron ore waste worsens the compressive strength. The best strength values were obtained for 20% IOT, 15% GGBS, 15% fly ash, and 40% slag sand samples [24].

<u>Copper ore waste</u>
Research on the use of copper ore waste is conducted on materials from various regions of the world. Scientists

https://doi.org/10.32933/ActaInnovations.36.4• ISSN 2300-5599 •

are conducting research on the production of ecological bricks that are formed in the process of geopolymerization. The production of these materials is based on mixing an alkaline solution with copper ore waste, then forming the resulting mass by pressing under a certain pressure in a mold at a slightly elevated temperature. The tests cover physical and mechanical properties by means of water absorption and compression tests, microstructure testing on a scanning electron microscope and X-ray diffraction analysis. The obtained results show that this waste can be used as materials for the production of geopolymers [25].
The development of new technologies affects the search for alternative experimental solutions for geopolymer binder. Research is conducted not only in relation to building materials but also materials used in road construction. The literature gives examples of tests of copper ore waste mixtures and low calcium slag. Research is often based on the influence of the content of individual components and the development of mechanical properties. An experimental study was carried out on a geopolymer binder based on copper mine waste, low calcium slag and sodium silicate solution. Variable values of individual components and solution concentration allowed to obtain the highest compressive strength 23.5 MPa, for 50% blast furnace slag, 10 molar NaOH concentration and curing at 60 °C for seven days. These studies allow further development of the use of copper ore waste as a geopolymer binder 26].

<u>Chromite ore</u>
Chromite ore is industrial waste produced during the production of chromium salts. Due to leaching, Cr (VI) is considered toxic and very dangerous. Further processing of this material involves the neutralization and protection of Cr in the ore. Despite this, scientists are attempting to use this waste in the production of geopolymers, which is associated with the neutralization of chromite ore. This is done on the basis of blast furnace slag, obtaining material that can potentially be used construction [27].
Literature analysis has shown an example of waste testing for use in the production of geopolymers, carried out with sodium sulfate and a geopolymer based on metakaolin, which may dispose of the residue after processing. Concentrated Cr leaching from the resulting samples was used, followed by X-ray / dispersion X-ray (SEM / EDX) scanning spectroscopy and X-ray photoelectron spectroscopy (XPS), which showed a reduction of CR (VI) to CR (III). The compressive strength of the obtained samples was higher than 42 MPa [28].
Another example of the study is an attempt to neutralize waste from chromite ore using composite materials, namely fly ash, blast furnace slag and metakaolin, based on a geopolymer correlated with zero-valent iron. X-ray diffraction studies and observations on a scanning electron microscope with an energy dispersion spectrometer showed effective immobilization of the chromite ore [29].

<u>Red mud from aluminum production</u>
This material is becoming a big problem for the environment and the degree of its use is negligible. In the production of 1 ton of aluminum, about 2 tons of red mud is generated [30]. It has a complex chemical composition, among which you can mention: iron, aluminum, silicon, calcium, sodium with the highest concentrations.

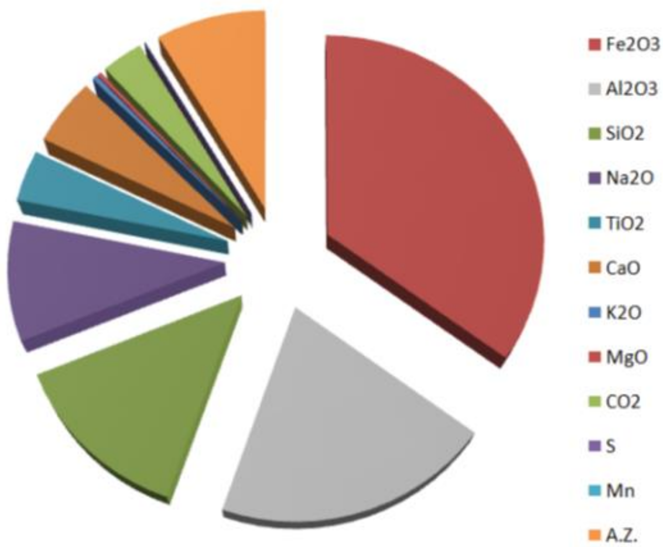


Fig. 2. Red mud chemical composition. *Source: [30].*

One of the modern applications of red sludge is its implementation as a raw material for the production of geopolymer cements [31]. An additional advantage of this waste is the fact that it is many times cheaper than e.g. metakaolin [11]. Research on the use of this material for the production of geopolymers mainly concerns its combination with other components, i.e. fly ash [32]or slag [33], as well as gangue from hard coal mining [11] [34], although it is possible to make geopolymer cement from red mud only. The production of alkali-activated material takes place with a pre-treatment process followed by activation, which is possible both through thermal activation - calcination and mechanical activation - grinding the raw material. Both processes are characterized by energy consumption, resulting in increased costs and a negative impact on the environment [33] [34]. After adding fly ash, the geopolymer prepared with the use of gangue, red mud with a sodium silicate solution can achieve a compressive strength of 7.3 MPa [35].

The compressive strength of geopolymers based on waste materials are summarizes in Table 1.

Table 1. Compressive strength of geopolymers based on waste materials.

Kind of waste	**Compressive strength [MPa]**	***Source***
Coal gangue, sodium silicate	20.19	*[18]*
60% coal gangue, 40% blast furnace slag, sodium silicate	40.18	*[18]*
60% coal gangue, 40% blast furnace slag, 2,5-20% slaked lime, sodium silicate	60.24	*[18]*
Iron ore waste, glass wool	>100	*[22]*
30-50% iron ore waste, 25-45% blast furnace slag, 5% slaked lime, sodium silicate	N/A	*[24]*
Iron ore waste, fly ash, slag sand, blast furnace slag, sodium silicate	N/A	*[24]*
Copper ore waste, slag with calcium content, sodium silicate	23.5	*[26]*
Chromite ore, metakaolin, sodium sulfate	>42	*[28]*
Chromite ore, fly ash, blast furnace slag, metakaolin	N/A	*[29]*
Red mud, coal gangue, fly ash, sodium silicate	7.3	*[35]*

The best properties from the given measurable values are characterized by geopolymers based on iron ore with glass wool, which achieve the required compressive forces above 100 MPa. A set of high temperature properties of marked materials in which the composition includes gangue with slag and lime dependence - 60.24 MPa, or gangue with 40.18 slag alone. The lowest available number of samples from the last group of commonly discussed and nominated sludge, gangue, fly ash - 7.3 MPa.

There are many advantages for which it is worth becoming interested in the topic of replacing traditional natural materials with mining waste. The table shows both the pros and cons of using these raw materials

Table 2. Advantages and disadvantages of using waste materials for the production of geopolymers.

Advantages	**Disadvantages**
Reducing the amount of waste in landfills [16]	Coal gangue requires proper activation [17]
Saving natural resources [3]	Several-stage pre-treatment of iron ore waste required due to the content of elements harmful to health [23]
Availability of raw materials and their lower cost [12]	The use of chromite ore before application involves the neutralization and protection of Cr in the ore [27]
Binding of heavy metal elements [23, 27]	The use of red sludge is energy intensive and expensive due to pre-treatment processes and alkali activation [34]
Elimination of the risk to the soil and water environment [16]	The properties of the obtained material depend on the base material

The research on the use of waste materials as raw materials for the production of geopolymers presented in this article requires large financial contributions for further development and adaptation to the regional conditions of individual countries. The search for appropriate technologies and implementation to domestic markets is associated with the strengthening of cooperation between research and development centers and enterprises from the industrial sector. Undoubtedly, the advantages that may encourage the implementation of such projects are the measurable benefits for the environment, as well as the implementation of innovations, which may become the main factor of competitiveness on the economic market. Preparation and application of a technological solution requires a number of requirements specified by the legal regulations of a given country. Hence, the strategy of managing the technological process and favorable system conditions (regulations and legal acts) is important. From the point of view of implementing the selected solution, it is important to choose the right raw material, because the properties of the final product are strongly dependent on the chemical stability and appropriately used additives. The analysis of the economic sector and the demand will allow to assess the choice of the market (local, national, international), where, when exporting items, the determinant will be transport costs and the so-called "Carbon footprint".
Geopolymerization process with the use of waste materials is a method of neutralizing hazardous substances in post-process materials. This allows for economic and ecological efficiency at the same time. On the one hand, the obtained product can replace traditional Portland cement, and on the other hand, it can be used to secure landfills [36].

Geopolymers based on waste materials can be used in the production of heat-resistant materials, thermal insulation, protective coatings for industrial pipelines and chimneys, or load-bearing materials for the stabilization of toxic waste [37] [38]. The increasing technological progress in the use of these raw materials will allow for the development of more and more modern courses for their management, which over time becomes a necessity [39].

Impact

The dynamic development of the construction, mining and processing market forces the search for new solutions and technologies to combine these areas in the field of the circular economy. Sustainability and circular economy policy are main factor for the development of sustainable construction materials for decreasing environmental impact of construction industry. They are also main motivators to research works on new, innovative materials' solutions for replacement traditional Portland cement technology [40]. Contemporary, the technology of Portland cement is widely used, but it has many disadvantages such as [41] [42]:

- energy- and non-renewable natural resource-intensity
- intolerable volume of CO2 emissions
- and questionable durability.

Geopolymerization seems to be most promise alternative solutions are traditional technologies used in cement industry [40]. The processes of pretreatment, alkaline activation and heat curing influence the total GHG emissions in the production of geopolymers. However, this area is still under investigation and depends on the location of the experiments carried out. Research is also carried out in terms of the optimization of greenhouse gas emissions, costs, availability and strength properties, so that the solutions found are sustainable in their use in terms of economy, environment and durability. The data that were obtained and which compare the CO2 emissions in the production of Portland cement with the production of geopolymer cement show that the production of 1 ton of geopolymer material emits 0.184 tons of CO2 from the combustion of coal fuel, compared to 1 ton of CO2 for Portland cement. [43]. These technologies have much lower carbon footprint than traditional construction materials. It is estimated that the manufacturing of geopolymers produced 6 times less CO2 than Portland cement [44].

The challenge in the production of geopolymers is the replacement of natural resources (metakaolin, slag, fly ash from coal combustion, volcanic tuff), mining waste and thus their management going hand in hand with environmental protection. From an economic point of view, the replacement of the above materials leads to the development of geopolymers due to cheaper waste raw materials. Geopolymerization is also an exciting technology that allows the use of different wastes streams (hazardous and non-hazardous) in geopolymer production [27] [34].The presented article presents the possibilities of using waste materials from hard coal and metal ores mining, as well as from the process of processing mineral resources as a material for the production

https://doi.org/10.32933/ActaInnovations.36.4• ISSN 2300-5599 •

of environmentally friendly composites. The growing importance of sustainable development of materials intended for buildings with low environmental impact and greater environmental awareness are the main determinants mobilizing research on the use of recyclable materials [45].

Nowadays, the replacement of metakaolin and fly ash by waste materials are important factor for possibilities geopolymer implementation. The high quality fly ash, especially class F, become valuable raw material for concrete industry. Because of that the process of this by product become higher and higher. There is a need investigation the new raw materials for that purpose. Moreover, this kind of approach is in line with the Strategic Implementation Plan of the European Innovation Partnership on Raw Materials [46], especially by ensuring the sustainable supply of raw materials to the European economy whilst increasing benefits for society as a whole. The additional value for this approach is to change the way of thinking about these waste materials and, by recycling, those complex products that contain many valuable raw materials create a more sustainable future. Through the use of waste and by-products the geopolymers could help reducing import dependency by improving supply conditions from EU, especially diversifying raw materials sourcing and improving resource efficiency (including recycling) and finding alternative raw materials came from wastes [47] [48].

The other important aspect is economic feasibility. In case of geopolymer it is quite complex problem. The price of material is dependent of such factor as:

- Used raw material, including cost of transportation [48]
- Used alkali activator; nowadays, this is the most unpredictable factor for long-term investments, because of huge changes [48]
- Price of energy
- Local regulations “greenhouse gas”, including “environmental” fees connected with waste management and greenhouse gas emission.

Conclusions

Geopolymers can be called "green material" because of the possibility of producing them with waste depending on the mining and mining industries. An additional advantage is the low CO2 emissions when used for port cement.

Within the article, the technical solutions for reuse and recycling of mine tailings, as well as process for other types of waste aim to integrate them in building products was explored. The analysis carried out in the article shows the possibilities of mineral waste management from mining and processing into materials that can be used in the wider construction industry. Materials obtained in the geopolymerization process are characterized not only by proper mechanical properties, but also by a number of features, i.e. binding of heavy metal elements or fire resistance. Such properties predestine the obtained product also for applications as so-called special materials. Examples of possible applications are landfill protection. Where materials often have corrosive effects. Refractory properties suggest that this material may also be used in mining. The solutions presented are currently at the prototype stage. The technologies developed require significant expenditure on their development and adaptation to local conditions prior to their application. The analyzed examples of using waste materials as raw materials to create new materials for construction and transport are a promising future perspective.

Conflict of interest

There are no conflicts to declare.

Acknowledgments

The presented works were carried out as part of the project: "Geopolymer foams with low thermal conductivity produced on the basis of industrial waste as an innovative material for the circular economy", which is financed by the National Center for Research and Development under the LIDER X program, contract number LIDER / 31/0168 / L-10/18 / NCBR / 2019, implementation period: 01/01/2020 - 30/11/2022.

References

[1] Eurostat, waste statistic [https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics – access 20.04.2020]

[2] Państwowy Instytut Geologiczny, 2019 Odpady wydobywcze: [http://geoportal.pgi.gov.pl/odpady – access 20.04.2020]

[3] Galhano C, Lamas P, Seixas D. Use of Industrial Waste for the Optimization of Ceramic Construction Materials in RICON19 - REMINE International Conference on Valorization of mining and industrial wastes into construction materials by alkali-activation. KnE Engineering (2020), 36–48
[4] Sedira N, Castro-Gomes J. Strength Development and Pore Structure Characterisation of Binary Alkali-activated Binder Based on Tungsten Mining Waste in RICON19 - REMINE International Conference on Valorization of mining and industrial wastes into construction materials by alkali-activation. KnE Engineering (2020), 73–85.
[5] http://www.fao.org/worldfoodsituation/csdb/en/ [access 05.06]
[6] Singh B. 13-Rice husk ash Waste and Supplementary Cementitious Materials in Concrete Characterisation, Properties and Applications. Woodhead Publishing Series in Civil and Structural Engineering (2018), 417-460
[7] https://www.biosil.vn/single-post/Goodyear-using-rice-husk-ash-in-tyre-manufacturing
[access 05.06.2020]
[8] Davidovits J, Davidovics M. Geopolymer: Room-temperature ceramic matrix for composites. In: Proceedings of 12th Annual Conference on Composites and Advanced Ceramic Materials, USA. (1988), pp. 835-842.
[9] Davidovits R, Pelegris Ch, Davidovits J. Standardized Method in Testing Commercial Metakaolins for Geopolymer Formulations, Technical Paper #26-MK-testing. Geopolymer Institute Library (2019)
[10] Król MR, Błaszczyński TZ, Geopolimery w budownictwie. Izolacje. 18 (2013), 38-43.
[11] Geng J, Zhou M, Li Y, Chen Y, Han Y, Wan S, Zhou X, Hou H. Comparison of red mud and coal gangue blended geopolymers synthesized through thermal activation and mechanical grinding preactivation. Construction and Building Materials. 153 (2017), 185–192
[12] Provis JL, Palomo A, Shi C. Advances in understanding alkali-activated materials. Cement and Concrete Research 78 (2015), 110–125.
[13] Heo UH, Sankar K, Kriven WM, Musil SS. Rice husk ash as a silica source in geopolymer formulation, in: V, Kriven WM, Zhou D, Moon K, Hwang T, Wang J, Lewinssohn C, Zhou Y. (Eds.) Developments in Strategic Materials and Computational Design, Ceramic Engineering and Science Proceedings 38 (2015), 87-102.
[14] Mikuła J, Łach M. Potencjalne zastosowania glinokrzemianów pochodzenia wulkanicznego Czasopismo Techniczne 8 (2012), 111-124.
[15] Zhang YI, Ling TC. Reactivity activation of waste coal gangue and its impact on the properties of cement-based materials – A review. Construction and Building Materials 234 (2020), 117424.
[16] Klojzy-Karczmarczyk B, Mazurek J. Propozycje rozszerzenia działań celem zagospodarowania materiałów odpadowych z górnictwa węgla kamiennego. Zeszyty Naukowe Instytutu Gospodarki Surowcami Mineralnymi i Energią Polskiej Akademii Nauk 98 (2017), 151–166.
[17] Li C, Wanb J, Suna H, Li L. Investigation on the activation of coal gangue by a new compound method. Journal of Hazardous Materials 179 (2010), 515–520
[18] Sedira N, Castro-Gomes J, Kastiukas G, Zhou X, Vargas A. A Review on Mineral Waste for Chemical-Activated Binders: Mineralogical and Chemical Characteristics. Mining Science 24 (2017), 29−58.
[19] Huang G, Ji Y, Li J, Hou Z, Dong Z. Improving strength of calcinated coal gangue geopolymer mortars via increasing calcium content. Construction and Building Materials 166 (2018), 760–768.
[20] Zhang W, Dong C, Huang P, Sun Q, Li M, Chai J. Experimental Study on the Characteristics of Activated Coal Gangue and Coal Gangue-Based Geopolymer. Energies 13 (2020), 2504.
[21] Li J, Wang J. Comprehensive utilization and environmental risks of coal gangue: A review. Journal Cleaner Production 239 (2019) 117946.
[22] do Carmo e Silva Defáveri K, Figueiredo dos Santos L, Franco de Carvalho JM, Fiorotti Peixoto RA, Brigolini GJ. Iron ore tailing-based geopolymer containing glass wool residue: A study of mechanical and microstructural properties. Construction and Building Materials 220 (2019), 375-385.
[23] Duan P, Yan C, Zhou W, Ren D, Development of fly ash and iron ore tailing based porous geopolymer for removal of Cu(II) from wastewater. Ceramics International, 42 (2016), 13507-13518.
[24] Das P, Matcha B, Hossiney N, Mohan MK, Roy A, Kumar A. Utilization of Iron Ore Mines Waste as Civil Construction Material through Geopolymer Reactions, Geopolymers and Other Geosynthetics. Mazen Alshaaer and Han-Yong Jeon, IntechOpen (2018)
[25] Ahmari S, Zhang L, Production of eco-friendly bricks from copper mine tailings through geopolymerization. Construction and Building Materials 29 (2012), 323-331.
[26] Manjarrez L, Nikvar-Hassani A, Shadnia R, Zhang L, Experimental Study of Geopolymer Binder Synthesized with Copper Mine Tailings and Low-Calcium Copper Slag. Journal of Materials in Civil Engineering 31 (2019)
[27] Huang X, Huang T, Li S, Muhammad F, Xu G, Zhao Z, Yu L, Yan Y, Li D, Jiao B. Immobilization of chromite ore processing residue with alkali-activated blast furnace slag- based geopolymer, Ceramics International 42 (2016), 9538-9549.

[28] Sun T, Chen J, Lei X, Zhou C. Detoxification and immobilization of chromite ore processing residue with metakaolin-based geopolymer. Journal of Environmental Chemical Engineering 2 (2014), 304-309.
[29] Huang X, Muhammad F, Yu L, Jiao B, Shiau YC, Li D. Reduction/immobilization of chromite ore processing residue using composite materials based geopolymer coupled with zero-valent iron. Ceramics International 44 (2018), 3454-3463.
[30] Burduhos Nergis DD, Abdullah MMAB, Vizureanu P, Tahir MFM. Geopolymers and Their Uses: Review. IOP Conference Series: Materials Science and Engineering 374 (2018), 012019
[31] Liu Y, Lina C, Wu Y. Characterisation of red mude derived from a combined Bayer Profess and bauxite calcination method. Journal of Hazardous Materials 146 (2007), 255-261.
[32] Jamieson EJ, Penna B, van Riessen A, Nikraz H. The development of Bayer derived geopolymers as artificial aggregates. Hydrometallurgy 170 (2017), 74–81.
[33] Ye J, Zhang W, Shi D. Effect of elevated temperature on the properties of geopolymer synthesized from calcined ore-dressing tailing of bauxite and ground-granulated blast furnace slag. Construction and Building Materials 69 (2014), 41–48.
[34] Geng J, Zhou M, Zhang T, Wang W, Wang T, Zhou X, Wang X, Hou H. Preparation of blended geopolymer from red mud and coal gangue with mechanical co-grinding preactivation. Materials and Structures 50 (2017), 109.
[35] Koshy N, Dondrob K, Hu L, Wen Q, Meegoda JN. Synthesis and characterization of eopolymers derived from coal gangue, fly ash and red mud. Construction and Building Materials. 206 (2019), 287–296.
[36] Stefańska A, Łach M, Mikuła J. Geopolimery jako przykład możliwości zagospodarowania odpadów. Nowoczesne technologie XXI w. – przegląd, trendy i badania. Tom 1. Wydawnictwo Naukowe Tygiel (2019), 24-34.
[37] Yunsheng Z, Wei S, Qianli C, Lin C. Synthesis and heavy metal immobilization behaviors of slag based geopolymer. Journal of Hazardous Materials 143 (2017), 206–213.
[38] Mierzwiński D, Łach M, Mikuła J. Alkaliczna obróbka i immobilizacja odpadów wtórnych ze spalania odpadów. Inżynieria Ekologiczna, 18 (2017), 102-108.
[39] Stępień M, Białecka B, Inwentaryzacja innowacyjnych technologii odzysku odpadów energetycznych (Stocktaking of innovative energy waste recyckling technologies). Systemy Wspomagania w Inżynierii Produkcji 6 (2017), 108--123.
[40] Łach M, Mierzwiński D, Korniejenko K, Stanek A, Mikuła J. The behaviour of alkali activated materials based on calcium clay at elevated temperatures. MATEC Web of Conferences 247 (2018), 00054.
[41] Palomo A, Krivenko P, Garcia-Lodeiro I, Kavalerova E, Maltseva O, Fernández-Jiménez A. A review on alkaline activation: new analytical perspectives. Materiales de Construccion 64 (2014), e022.
[42] Assaedi H, Shaikh FUA, Low IM Effect of nanoclay on durability and mechanical properties of flax fabric reinforced geopolymer composites. Journal of Asian Ceramic Societies 5 (2017), 62-70.
[43] Davidovits J. Environmentally Driven Geopolymer Cement Applications. Geopolymer 2002 Conference, (2002) Melbourne, Australia.
[44] Mikuła J, Korniejenko K. (Eds.) Innovative, cost effective and eco-friendly fibre-based materials for construction industry (Cracow, Wyd. Politechniki Krak.) 2015.
[45] Sikapizye E, Habanyama A. Synthesis and characterization of hemp and flax fiber reinforced geopolymer composites. Journal of Chemical Engineering and Materials Science 11 (2020), 10-23.
[46] https://ec.europa.eu/growth/sectors/raw-materials/eip_en – access 20.08.2020]
[47] Yao Y, Hu M, Di Maio F, Cucurachi S. Life cycle assessment of 3D printing geo-polymer concrete An ex-ante study. Journal of Industrial Ecology 24 (2020), 116-127.
[48] Bumanis G, Vitola L, Pundiene I, Sinka M, Bajare D. Gypsum, Geopolymers, and Starch—Alternative Binders for Bio-Based Building Materials: A Review and Life-Cycle Assessment. Sustainability 12 (2020), 5666.
[49] https://www.icis.com/explore/commodities/chemicals/caustic-soda/ – access 20.08.2020]

ECONOMIC, SOCIAL AND ENVIRONMENTAL IMPACTS ATTAINED BY THE USE OF THE EFFLUENTS GENERATED WITHIN A SMALL-SCALE BIOREFINERY CONCEPT

Tiago F. Lopes*
Laboratório Nacional de Energia e Geologia, I.P., Unidade de Bioenergia e Biorrefinarias, Estrada do Paço do Lumiar 22, 1649-038 Lisbon, Portugal, tiago.lopes@lneg.pt
https://orcid.org/0000-0002-9720-8777

Rafał M. Łukasik
Laboratório Nacional de Energia e Geologia, I.P., Unidade de Bioenergia e Biorrefinarias, Estrada do Paço do Lumiar 22, 1649-038 Lisbon, Portugal, rafal.lukasik@lneg.pt
https://orcid.org/0000-0002-7805-5744

Abstract
Biorefineries are emerging as the proper route to defeat climate change and other social, socio-economic and environmental concerns. So far, no residual lignocellulosic biomass-based biorefineries have been yet industrially implemented, mainly due to its economic viability. This article exposes some elements that may help overcome the bottlenecks associated to its social, economic and environmental sustainability: small-scale approaches, biomass valorisation through added-value products and near-zero effluent.

Keywords
biorefinery; biomass; effluents; economic; sustainability; impact

Introduction

The energy sector stands out for its significant impact and transversal role it plays in all other economic sectors, sustainable development, and challenges identified under the European Strategic Plan for the Energy (SET-PLAN). The energetic valorisation of biomass, as renewable natural resource, intends to play a role central to the future of Energy Policies, in particular for the decarbonisation of the transport sector and its more efficient use in the production of electricity and in the heating and cooling.
Fossil fuels depletion and climate change, as well as the current global energy demands require the search for suitable bio-substitutes for the products currently being obtained from fossil sources [1]. In the EU context, the Renewable Energy Directive (RED II) has established a share of 32 % as the overall target for Renewable Energy Sources consumption by 2030, with a minimum of 14 % of the energy consumed in road and rail transport coming from renewable energy [2]. This directive also defines some sustainability and GHG emission criteria. For instance, in the case of transport biofuels, after January 2026, a minimum of 65 % GHG reduction must be achieved in comparison to reference fossil fuels. Similarly, considering that biofuels production may lead to the extension of agricultural land into non-cropland and negatively affect areas with high carbon stock, indirect land use change (ILUC) issues have also been included and regulated in RED II.

First-generation (1G) biofuels suffer of important drawbacks to meet those criteria due to the high water and energy consumption needed during their production and the negative side effects on the food market. Hence, during the past decade there has been a growing interest in developing biofuels and bioenergy carriers non-linked to the food sector. For biofuels productions (e.g. bioethanol), the use of residual lignocellulosic biomass (second-generation, 2G ethanol) instead of food crops (1G ethanol) can lead to lower environmental impacts (and no competition with food crops) [3]. In this line, and within the 14 % transport sub-target, RED II has established that the contribution of advanced biofuels should be of at least 3.5 % in 2030 (Fig. 1). This category represents biofuels produced from non-food related and sustainable feedstocks, such as energy crops, algae and wastes, as well as agricultural and forestry residues.

https://doi.org/10.32933/ActaInnovations.36.5• ISSN 2300-5599 •

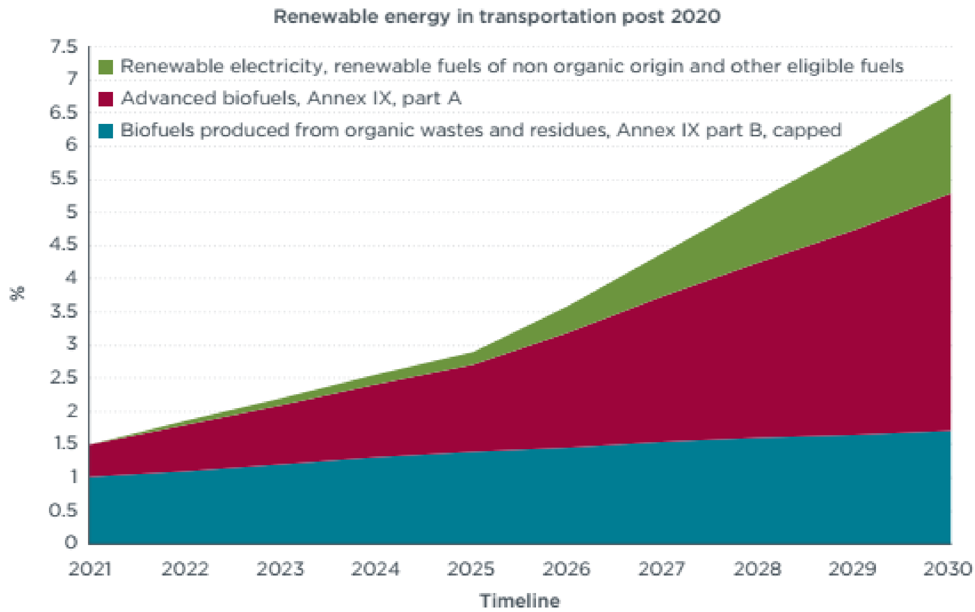


Fig. 1. the RED II requirement for fuel suppliers to have a 1.5% minimum energy share for the overall renewable energy mandate beginning in 2021, which includes a 0.5% minimum share for advanced biofuels produced from the feedstocks listed in Annex IX, Part A. The overall share of biofuels produced from Annex IX, Part B, can be smaller than 1.0%–1.7%, as indicated in the figure. *Source: The European Commission's Renewable Energy Proposal For 2030, ICCT - International Council on Clean Transportation, January 2017* [4]

One way to overcome these concerns is the development of biorefining processes to produce biofuels and bioproducts with a lower global warming potential (GWP). A biorefinery is an industrial installation that optimises the full use of biomass (raw material) in a sustainable way giving rise to a diverse range of products, namely biofuels, energy, biomaterials and chemicals (end-use or intermediates). It has evident similarities with a refinery that uses fossil resources (e.g. oil) and in certain situations, constitutes a viable alternative to replace oil with biomass. Although the characteristic of a biorefinery is a multi-product industrial unit, like an oil refinery, its integrative design varies among those that are primarily energy-based, that is, in which the industrial unit is optimized primarily to generate bioenergetic products from biomass, namely biofuels, electricity and heat, generating simultaneously co-products that could be precursors of products of greater added value for non-energy applications; and those that are optimised for generate mostly bioproducts (biomolecules, intermediate chemicals) and biomaterials from biomass and in parallel only a minority fraction of the biomass is diverted to production biofuels, electricity and/or heat, as that is not the main purpose of a biorefinery. Biorefineries have primarily followed the concept of classical oil refineries, using a single feedstock in huge processing capacities to achieve maximum economy of scale, but under such framework, the opportunities for installing such biorefineries in most rural areas in Europe and even worldwide are scarce. Studies have revealed that the main bottlenecks are associated to high CAPEX and OPEX, and very often to the inexistence of a sustainable biomass supply at regional level [5].

Small-scale biorefineries have been proposed as a potential solution to overcome most of these challenges, since when located in rural areas they can promote territorial economic cohesion and generate local direct and indirect jobs [6,7]. Small-scale also allows a reduction in transportation costs of raw materials and intermediate products and leads to a direct link between industry and the primary sector. Despite the strategic relevance of small-scale biorefineries, numerous technological and strategic challenges still hamper commercial development, namely the heterogeneity of the biomass resources for further processing [8].

Furthermore, several studies have proven that in order to become economically and environmentally viable, it is almost mandatory that these small-scale biorefineries valorise all the available effluents (wastewaters, gas emissions, waste solids, etc.) for producing additional added-value products and reduce the consumption of external energy sources [9–12]. Lopes et al. [13] have demonstrated that for a microalgae-based biorefinery,

https://doi.org/10.32933/ActaInnovations.36.5• ISSN 2300-5599 • © 2020 RIC Pro-Akademia – CC BY

using genetically modified cyanobacteria for direct production of ethanol, the process is only economically viable when the pigments and proteins obtained from microalgae biomass are recovered, and the spent biomass sent to anaerobic digestion for biogas production and subsequentially used in co-generation. Susmozas et al. [14] also state that for a small-scale biorefinery using olive tree pruning as feedstock, the bioethanol production together with the integrated by-products production (xylitol and antioxidants) is technically and economically viable, and the energy demands are reduced by power and steam co-generation from combustion of residual solid material and methane produced by anaerobic digestion of wastewater.

Process modelling and simulation using software-based tools is a useful methodology to ascertain process feasibility at scales larger than laboratory scale, such as pilot, demo and industrial scales [10,15,16]. The use of process modelling to study biomass processes for the production of high added-value products has certain limitations on evaluating scalability and replicability. Usually, process modelling is based in black-box models where process yields are taken from the literature or from experimental data, so they cannot evaluate the consequences of changing feedstock properties, process parameters and operational conditions. Thus, there is an inherent need of knowing more about the fundamentals of these processes:

- biomass composition models using realistic and predictive models, where biomass reactivity can be represented by the reactivity of a series of surrogate molecules
- actual predictive models that can predict the mass and energy balances of biomass-based processes through kinetic, thermodynamic and semi-empirical models.

These approaches allow the evaluation of different scenarios, assessing which pathway is the most adequate when upscaling a biorefinery, for the process to present lower CAPEX and OPEX, and for lower environmental and social (negative) impacts.

As an example, it is known that in rural temperate and humid tropical regions, most biomass resources are crop and food residues, animal and human waste and agro-processing residues. One way to take advantage of this heterogeneity is by combining two different biorefinery platforms: the biochemical platform transforming lignocellulosic feedstock into sugars and then into biofuels and/or added value chemicals, and the anaerobic digestion platform converting wet biomass into biogas [17]. Such a small-scale integrated biorefinery should be able to transform both dry and wet biomass residues by means of different processes to produce an array of bioproducts, maximizing the resources, the energy efficiency and the environmental sustainability of the whole value chain. Lopes et al. [9] have shown through a comparative process modelling and simulation study that, by combining these two different platforms (lignocellulosic-based small-scale biorefineries, integrated with a piggery waste-based anaerobic digestion platform, located in Portugal and Chile – Fig. 2), the isobutene/xylo-oligosaccharides (XOS) biorefinery concept is proven to be economically viable in both countries, mainly due to the high market value of XOS, and is a flexible process that can be implemented in any of these countries, even using different lignocellulosic biomass as feedstock (wheat straw and corn stover).

Therefore, techno-economic analysis (TEA) of biorefineries as well as life cycle assessment (LCA) are two powerful tools to evaluate the expected impacts (social, economic and environmental) of implementing innovative bio-based conversion routes for the production of biofuels and/or bio-based products. Usually these assessments are bioenergy-driven, and tend to demonstrate that its economic viability is highly dependent on the main product market price or by significantly reducing the energy consumption of biomass fractionation or downstream processing units (e.g. hydrothermal biomass pre-treatment, ethanol/water distillation process). Furthermore, by funnelling the biomass conversion entirely to biofuels, there are two main bottlenecks: market-dependency and excess of effluent streams to be treated (gaseous, liquid or solid). The former is extremely oscillating and with a decreasing trend on biofuels market price, the latter generates higher CAPEX and OPEX for waste treatment and additional negative environmental impacts. To overcome these drawbacks, it is of extreme importance to valorise all the biomass fractions and perform mass and heat integration to reduce or eliminate the effluent streams

https://doi.org/10.32933/ActaInnovations.36.5• ISSN 2300-5599 •

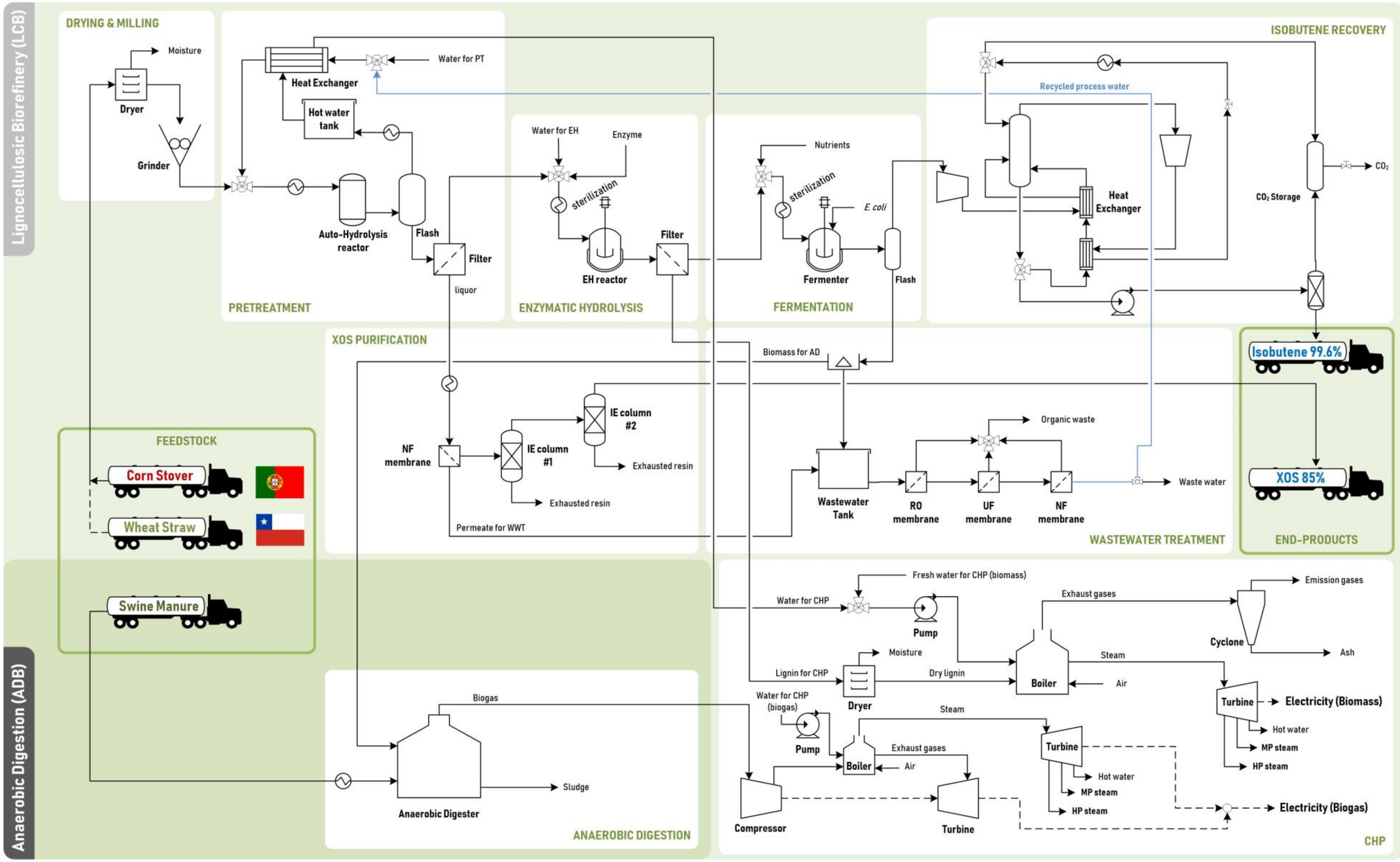


Fig. 2. Example of an integrated small-scale biorefinery concept for valorisation of all streams. *Source: Adapted from [9]*

Agricultural and forest residues, like any other plant biomass, consist of three main macromolecules: cellulose, hemicellulose and lignin [18]. To efficiently convert this biomass feedstock into biofuels (such as 2G bioethanol) and bioproducts (biorefinery-driven), pre-treatment is the first technological operation, in order to make the biomass susceptible to hydrolysis with the aid of enzymes. The resulting C6 sugars syrup is then fermented and transformed into 2G bioethanol, higher alcohols, or bio-based products. C5 sugars can be fermented together with C6 sugars (using recombinant strains) or upgraded into, for instance, prebiotics (e.g. XOS). Lignin can be burned to generate steam (and therefore reduce the energy demand and the use of fossil sources) or preferably can also be valorised into added-value products (e.g. vanillin, benzene-toluene-xylene, syringol, carbon fibres or activated carbon). Mass integration through the re-use of carbon dioxide effluent streams from fermentation for microalgae cultivation, anaerobic digestion of waste water streams for biogas production or upgrading, use of biomass ash as in-situ catalyst, are interesting and promising options to reduce the impacts of such technologies. Heat integration between stream processes is also one of the most adequate pathways for taking advantage of biorefineries flexibility, leading to a considerable reduction on energy consumption.

Impact

Considering the economics of advanced biorefineries, it is necessary to warn that in the more restricted scope of advanced biorefineries focused on energy recovery, they almost all require incentives through stable medium and long-term legislative measures. In particular, the cost of production of advanced biofuels depends mainly on the cost of biomass (raw material), investment cost and operating cost. The latter two are higher than the CAPEX and OPEX costs of first generation biorefineries (e.g. FAME biodiesel units). Among others reasons, the costs of collecting and transporting biomass are important to be considered in the initial planning phase of biorefineries, so only the value chains based on low cost, zero cost or residual biomass negative can currently offer the production of bioenergetic products competitive.

Furthermore, the economic impact attained by the use of effluents generated within a biorefinery concept is reflected on the reduction of additional investments costs in equipment for waste treatment, a reduction on operating costs (e.g. raw materials, utilities, maintenance) by lowering the needed volumes to be processed, achieving high energy-efficient yields on raw materials recovery and recycling, lowering the logistic and supply chain costs by using a small-scale biorefinery concept and therefore create local synergies with suppliers and end-users, without the need of utopic processes.

Additionally, a small-scale biorefinery concept taking advantage of all the generated effluents and valorising the biomass fractions generate much lower GHG emissions (virtually zero), have a significant impact on fossil fuels depletion (no fossil sources are needed – a small-scale biorefinery has the potential to be energy-sufficient), water depletion (a huge amount of fresh water needed is reduced by waste water recycling and purification), eutrophication and toxification (almost no toxic waste for soils and water is generated).

An adequate biorefinery design is crucial to prevent the toxic effluents and GHG emissions as in oil refineries design, where negative environmental and social impacts were obtained during oil processing and products use. Nevertheless, sustainable biorefinery systems are still a challenge since weak designs lead to processes hardly operating on the economic margin, not providing significant reduction of environmental burdens in comparison to petrochemical systems and facing socio-economic issues due to endless discussion on land use, labour, food safety, etc. The diversity of bioproducts that can be obtained from biomass under the biorefinery concept lies under the umbrella of bioeconomy. As Moncada et al. state: "A biorefinery is a complex system, where biomass is integrally processed or fractionated to obtain more than one product including bioenergy, biofuels, chemicals and high value-added compounds that only can be extracted from bio-based sources. The latter after a comprehensive study of the raw materials to be used and a sustainable design based on the latest state of the art technologies and approaches which include aspects of the three pillars of sustainability" [19]. Hence, in order to catch the same train as the European Commission and other policy makers, bioenergy and biorefinery researchers and players should look at these (near zero waste) small-scale biorefineries as a promising solution to a worldwide concern.

Another aspect in the small-scale advanced biorefinery development is territorial cohesion and territorial enhancement. It contributes to reduce the gap in the implementation of technology-based industries between more developed regions and generally less developed rural areas where biorefineries can boost both qualified employment and technology enhancement. However, the existence of residual biomass available in a given region is not in itself synonymous with the economic profitability of a biorefinery in that region. It is necessary to assess the constraints of your supply chain, alternative markets and industrial infrastructures in the biomass sector, which may already exist in that region that allows for the enhancement of local synergies, among others.

Conclusions

The 2030 horizon is the tolerable limit for implementing advanced biorefineries, focused on bioenergetic products, from residual biomass or with a lower economic value. Namely, biomass agroforestry waste or in the co-valorisation of biomass in industrial value-added bioproducts, obtained with or without biochemical or thermochemical processing of any other organic biomass provided it does not compete with the human food markets and within the so-called bioeconomy.

The valorisation of effluents is very likely to be a good option for GHG emission reduction. However, for reasons of fair competition, LCA methodologies should be applied in an identical way to assess the sustainability of both energy- and any other non-energy basis biorefineries, namely in terms of comparative measures to reduce GHG emissions.

Conflict of interest

There are no conflicts to declare.

Acknowledgments

This research has been carried out at the Biomass and Bioenergy Research Infrastructure (BBRI) – LISBOA-01-0145-FEDER-022059, supported by Operational Programme for Competitiveness and Internationalization (Portugal 2020), by Lisbon Portugal Regional Operational Programme (Lisboa 2020) and by North Portugal Regional Operational Programme (Norte 2020) under the Portugal 2020 Partnership Agreement, through the European Regional Development Fund (ERDF).

References

[1] Abas N, Kalair A, Khan N. Review of fossil fuels and future energy technologies. Futures 69 (2015), 31–49.

[2] EU Directive (EU) 2018/2001 of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. Official Journal of European Union (2018), 82–209.

[3] Maga D, Thonemann N, Hiebel M, Sebastião D, Lopes TF, Fonseca C, Gírio F. Comparative life cycle assessment of first- and second-generation ethanol from sugarcane in Brazil. International Journal of Life Cycle Assessment 24 (2019), 266–280.

[4] The European Commission's renewable energy proposal for 2030. ICCT - International Council on Clean Transportation. 2017.

[5] Chandel AK, Garlapati VK, Singh AK, Antunes FAF, da Silva SS. The path forward for lignocellulose biorefineries: Bottlenecks, solutions, and perspective on commercialization. Bioresource Technology 264 (2018), 264, 370–381.

[6] de Visser CLM, van Ree R (Eds.) Small-scale Biorefining. Wageningen University Research 2016.

[7] Loaiza SS, Aroca G, Cardona CA. Small-scale biorefineries: future and perspectives. in Torres I. (Ed.) Biorefineries: Concepts, Advancements and Research 2017, pp. 39–72.

[8] Balan V. Current Challenges in Commercially Producing Biofuels from Lignocellulosic Biomass. International Scholarly Research Notices (2014), 463074.

[9] Lopes TF, Carvalheiro F, Duarte LC, Gírio F, Quintero JA, Aroca G. Techno-economic and life-cycle assessments of small-scale biorefineries for isobutene and xylo-oligosaccharides production: a comparative study in Portugal and Chile. Biofuels, Bioproducts and Biorefining 13 (2019), 1321–1332.

[10] Mussatto SI, Moncada J, Roberto IC, Cardona CA. Techno-economic analysis for brewer's spent grains use on a biorefinery concept: The Brazilian case. Bioresource Technology 148 (2013), 302–310.

[11] Martínez-Ruano JA, Caballero-Galván AS, Restrepo-Serna DL, Cardona CA. Techno-economic and environmental assessment of biogas production from banana peel (Musa paradisiaca) in a biorefinery concept. Environmental Science and Pollution Research 25 (2018), 1–10.

[12] Moncada J, Cardona CA, Rincón LE. Design and analysis of a second and third generation biorefinery: The case of castorbean and microalgae. Bioresource Technology 198 (2015), 836–843,

[13] Lopes TF, Cabanas C, Silva A, Fonseca D, Santos E, Guerra LT, Sheahan C, Reis A, Gírio F. Process simulation and techno-economic assessment for direct production of advanced bioethanol using a genetically modified Synechocystis sp. Bioresource Technology Reports 6 (2019), 113–122.

[14] Susmozas A, Moreno AD, Romero-García JM, Manzanares P, Ballesteros M. Designing an olive tree pruning biorefinery for the production of bioethanol, xylitol and antioxidants: A techno-economic assessment. Holzforschung 73 (2019), 15–23.
[15] Moncada J, El-Halwagi MM, Cardona CA. Techno-economic analysis for a sugarcane biorefinery: Colombian case. Bioresource Technology 135 (2013), 533–543.
[16] Quintero JA, Moncada J, Cardona CA. Techno-economic analysis of bioethanol production from lignocellulosic residues in Colombia: A process simulation approach. Bioresource Technology 139 (2013), 300–307.
[17] Bharathiraja B, Chakravarthy M, Ranjith Kumar R, Jayamuthunagai J, Praveen Kumar R. Integrated Biorefinery for Bioenergy and Platform Chemicals. Platform Chemical Biorefinery (2016), 417–435.
[18] Wertz J-L, Bédué O. Lignocellulosic Biorefineries; 1st ed.; EPFL Press: Lausanne, Switzerland, 2013.
[19] Moncada BJ, Aristiztibal MV, Cardona CA. Design strategies for sustainable biorefineries. Biochemical Engineering Journal 116 (2016), 122–134.

https://doi.org/10.32933/ActaInnovations.36.5• ISSN 2300-5599 •

INFLUENCE OF MICROWAVE TREATMENT ON QUALITY PARAMETERS OF SNACKS FOOD. IMPACT ISSUEES.

Anna Goszkiewicz
Research and Innovation Center Pro-Akademia
95-050 Konstantynow Lodzki, Poland, anna.goszkiewicz@proakademia.eu
https://orcid.org/0000-0002-4620-1030

Ewa Kochanska
Research and Innovation Center Pro-Akademia
95-050 Konstantynow Lodzki, Poland, ewa.kochanska@proakademia.eu
https://orcid.org/0000-0002-4735-7969

Katarzyna Korczak
Research and Innovation Center Pro-Akademia
95-050 Konstantynow Lodzki, Poland, katarzyna.korczak@proakademia.eu
https://orcid.org/0000-0002-0216-8937

Volodymyr O. Potapov
Kharkiv State University of Food Technology and Trade,
Department of Power Engineering, Engineering and Physical and Mathematical Sciences
333, Klochkivska St., Kharkiv, 61051, Ukraine, potapov@bigmir.net

Svitlana Prasol
Kharkiv State University of Food Technology and Trade,
Department of Processes and Equipment of Food and Hotel and Restaurant Industry named after M. Belyaeva
333, Klochkivska St., Kharkiv, 61051, Ukraine, process229@ukr.net

Abstract

The following publication presents results of the research on a new, innovative, mild technology of food processing with microwaves technology in order to develop novel food in the form of “on the go” healthy snacks. Different aspects of microwave treatment technologies within the context of physical model of electromagnetic field interaction with a food product, marketing and energy aspects were considered. Furthermore, comparison of sensory quality of conventionally and microwave treated nuts was shown, which is a key feature of nuts, seeds and dried fruits for most consumers. A comparative LCA analysis of convectional and microwave roasting was performed as well.

Keywords

roasting, microwave, convection, nuts, sensory quality, LCA, economy

Introduction

Global market context

The food industry is constantly looking for new products and solutions, following customer expectations. One of the trends that has been observed for several years on the Polish and global market is introduction to the market products that are defined as “novel foods” [1]. The answer to this trend is the development of new production technologies that result in unique product features without the need to increase selling price of the products. Novel food is defined as innovative food, produced with the use of modern technologies and production processes.

The global healthy snacks “on the go” market is worth 389,228 million USD in 2020, and the nuts and seeds market segment will reach 9,841 million USD in 2020. The total market of snacks is projected to grow by 4.8% (CAGR 2020-2025) annually and by 3.0% (CAGR 2020-2025) for nuts and seeds [2]. According to the report "Worldwide Healthy Snack Food Market: Analysis and Industry Forecast 2022", the global snack market will reach 620 billion USD by 2021 with a cumulative annual growth rate of 5.8% [3].

The size and the expected growth of the market, anticipated by all market analysts mean that reducing the cost of the roasting process only in relation to energy inputs will bring global energy and environmental benefits, and consequently will be a source of the promising competitive advantage for the producers of healthy snacks.

The quality of food products is very important for consumers, as it affects their health and also determines the taste. Many methods of assessing the quality of such products have been developed [4]. These are organoleptic and instrumental methods. From the point of view of the majority of consumers, the most important quality feature of food products is taste. They are mainly assessed by organoleptic methods: sensory analysis or organoleptic evaluation.

Snack food appeared in consumer behaviour as an alternative to full-fledged meals. “Snacks” are defined as dried fruit, nuts, seeds, grains, chips, crackers, popcorn, salty sticks, bars, etc. This is due to the growing market share of people who pays a special attention to ecological, pro-health products and the convenience offer. For active people, the quality of the consumed products is of the greatest importance, and at the same time, they want snacks to be comfortable to use "on the go". The ingredients found in the products are important from the health point of view. Dried fruits contain a large amount of fibber, supporting the digestive system and protecting against atherosclerosis, obesity and cancer. At the same time, they have a low or moderate glycaemic index (GI), which is the effect of food on blood sugar levels. Nuts and seeds are a rich source of potassium, magnesium, and folic acid - they improve memory and concentration. They also contain unsaturated fatty acids that lower the level of bad cholesterol in the blood. Although nuts contain various substances that have cardio protective effects, their omega-3 fatty acid profile is at least partially responsible for the response to hyperlipidaemia.

The increasing concentration of consumers on the nutritional value of the product, such as high content of vitamins and proteins and low calories, works to the advantage and expanding of the market. Healthy snacks “on the go” are widely eaten in mature economies [5].

Increasing consumer pressure in Europe and North America first of all, on quality of health products “on the go” due to increasing consumer purchasing power, could strengthen the market in the coming years. The growing demand for snacks, combined with the rising purchasing power of customers, can stimulate market development.

Analysing the expectations of individual customers (consumers), regardless of the purchase motivation and the intended use of the product, the key feature of the dried nuts and seeds for the majority of consumers is taste. This is reflected in the KPMG report, which shows that for over 90% of the surveyed consumers the most important things are the taste and quality of the sweets and snacks they buy [6].

The growing awareness of consumers means that they consciously choose the available products, which are actually less processed, more natural and therefore - healthier. Active people attach particular importance to the quality of the consumed products, and at the same time, they want them to be comfortable to use "on the go".

Disposable snacks and drinks are increasingly consumed around the world due to the long working hours of the special group of consumers, so called “Millennials”. Millennials that is the baby boom generation of the 1980s and 1990s. Today's 20- and 30-year-olds represent over half of the reproductive age population in the world, approximately 1.7 billion people. Globally, the Millennials, regardless of their country of origin, have similar attributes. They are the group of consumers brought up in the online environment. The Millennial generation pays special attention to ecological and pro-health products and the convenience offer. Millennials are an increasingly important purchasing group for food producers, because today they largely make purchasing decisions (they expect new products, new forms of marketing etc.). Because of that, any food producer who thinks about the future is definitely including this segment of consumers in their activities and is trying to meet the new needs of increasing demand on healthy snacks eaten “on the go” which becoming more and more popular. The answer for this challenge is to increasing volume of sales, and make greater profits, however without necessarily increasing the selling price. It is advantageous when it fits in the "green economy" trend, since it can be used for marketing purposes [7].

<u>Research hypothesis</u>

In research on the development of a new food processing technology, dedicated to healthy snack products "on the go", and in particular – with regards nuts and seeds, it was hypothesized that the use of microwave roasting technology will improve the taste of the snacks and at the same time will result in energy savings.

The research hypothesis in relation to the taste values assumed that mixtures of nuts and seeds roasted under low-pressure microwave technology will be characterised with more favourable proportions of fatty acids and other nutritional values supporting the proper functioning of the body, than in conventional technologies.

https://doi.org/10.32933/ActaInnovations.36.6• ISSN 2300-5599 •

The research hypothesis in relation to the cost of energy of the roasting process assumed that the production costs of healthy snacks would be reduced through the use of microwave technology. Due to the fact, that microwaves operate across the entire cross-section and heat up products volumetrically, the duration of the roasting processes will be shortened, and the energy efficiency of the thermal treatment of nuts and seeds will be improved. The energy costs of the roasting processes of nuts and seeds account for from 1.5% of the final consumer price for e.g. in regards to cashew nuts and up to 6.7% for sunflower seeds [8].
Simultaneously the hypothesis with regard to the energy efficiency of the thermal process assumed that the use of microwave roasting technology would reduce the emission of harmful by-products, especially GHG emission.
There is no doubt that when food safety conditions are met, food sensory quality and price determine food selection and consumption. As soon as a complete supply of food is achieved - quantitatively and in terms of its diversity - the question of the motivation of consumer choice becomes an important marketing and nutritional problem. Hence, other research question concerns the effect of type of roasting on the sensory properties of nuts. Food selection is influenced by many interrelated factors. They relate to the food itself, the appearance, smell, texture and flavour; to the consumer - his individual preferences and aversion as well as psychological factors such as personality, beliefs (views), experiences and moods; finally, to external factors - economic, cultural and sociological. They all influence food choice and consumption. Sensory properties are by definition a phenomenon that arises because of the sensory perceptions of certain physical and chemical properties of food. The implication of the above is that they cannot be considered without connection to the human sensory apparatus. Sensory attractiveness of food products and meals prepared on their basis is the basic criterion for the acceptance of the product selection by the consumer. The set of features that create sensory attractiveness, apart from availability and health, contribute to the generally understood quality of a food product. These characteristics include taste, texture, odour, and appearance.
Combining the results of consumer research with the results of laboratory profiling of sensory quality allows for a rational modification of the existing ones and the development of new products of high quality in the opinion of consumers.

Physical model of electromagnetic field interaction with a food product during microwave treatment
The results of microwave processing depend on the interconnection of several factors, in particular, the generation of microwave energy, its transfer through the media, penetration into the product and conversion into heat. Current frequency and power output are two determining factors that are the most significant for microwave generator. Electromagnetic oscillation frequency is constant and, as a rule, frequency of 2450 MHz is mainly used for processing of food products.
During the work of microwave generator, strength of electromagnetic field in the media depend on its power output. Value of microwave energy that reaches the surface of food product depends to the product's volume, its geometrical dimensions and dielectric permeability.
Thermophysical and dielectric properties to a great degree depends on moisture capacity of a product. An increase in the number of water molecules causes an increase in dielectric losses and, as a consequence, more active heating. Dehydration of a product in the process of heating is followed by nonuniformity of moisture by volume. Whereby wetter sections obtain more quantity of energy but in consequence of moisture movement, its concentration equalizes. Gradual decrease in moisture content results in decrease of dielectric loss and, consequently, decrease of heat energy that is released in the product.
Thus, a set of thermophysical and dielectric properties determines resistance for transferring electromagnetic field, depth of penetration of electromagnetic field. Penetrating the product electromagnetic field strength is attenuated that results in decrease in heating rate of a product. As a rule, to maintain effective heating at the current frequency, products of thickness not more than 30-50 mm should be processed in most cases.
Thus, to ensure efficient work of microwave oven and obtain high quality products it is necessary to determine rational values of electromagnetic field strength depending on the output power of magnetron and physical properties of food product, that determine the depth of penetration of electromagnetic field in to the material.
The power absorbed by a product during microwave heating, on the one hand, depends on electric parameters of the field (current frequency and strength of electromagnetic field) and, on the other hand, on dielectric parameters of a product (dielectric loss factor and relative dielectric constant) and it is determined by the known formula

$$Q_d = 2\pi f \varepsilon_0 \varepsilon'' E^2, \qquad (1)$$

where Q_d is the power density of microwave absorbed per unit volume of the material, W/m^3; ε_0 is the permittivity of free space (8.85 · 10^{-12} F/m); f is microwave frequency, Hz, ε'' is the relative dielectric loss factor; E is the electromagnetic field strength in the medium (product), V/m.
Among the above-mentioned factors, electromagnetic field strength that can be regulated during microwave treatment has priority significance.
Our task is to determine electromagnetic field strength that is formed by microwave generator on the surface and inner layers of a product.

Let's to determine electromagnetic field on the surface of a food product, the following well-known electrodynamics equation is used [9]. The energy flux density of an electromagnetic wave transmitted by in an arbitrary medium is determined by the formula

$$\Pi = v_f \varepsilon \varepsilon_0 E^2 , \quad (2)$$

where Π is the energy flux density of electromagnetic wave in an arbitrary medium, W/m^2; $v_f = c/\sqrt{\varepsilon\mu}$ is the light velocity in the medium, m/sec; c is the light velocity in the vacuum; μ_0 is the magnetic constant (μ_0=4π·10^7 H/m); μ is the magnetic permeability of the medium.
In the working volume of microwave oven electromagnetic wave transfers practically at light velocity in vacuum because dielectric and magnetic permeability for air equals one (ε=μ=1). That is why energy flux density that is transferred from the microwave generator to the product equals

$$\Pi = c\varepsilon_0 E_0^{\ 2} , \quad (3)$$

where E_0 is magnitude of electric field in the microwave oven, V/m.
On the other hand, energy flux density of an electromagnetic wave on the surface of a product can determined as ratio of microwave generator power to surface area of a product, that is

$$\Pi = \frac{P}{S} , \quad (4)$$

where P is the power of microwave generator, W; S is the surface area of a product, m^2.
Equating the right-hand sides of expressions (4) and (3), we can obtain formula for calculating the magnitude of the electromagnetic field on the surface of the product

$$E_0 = \sqrt{\frac{P}{\varepsilon_0 c S}} . \quad (5)$$

Further let's define the magnitude of electric field that occurs in the product itself, which it differs from the electric field on the border of product because electromagnetic wave transfer rate on depends from dielectric properties of product. Under conditions of optimal loading of microwave oven all energy of electromagnetic waves is absorbed by the product, i.e. energy flux density Π does not change on the surface of a product. Then it is possible to write down next equality

$$v_f \varepsilon \varepsilon_0 E^2 = c\varepsilon_0 E_0^{\ 2} . \quad (6)$$

From here with regard of expression for light velocity in the medium we obtain

$$E^2 = \frac{E_0^{\ 2}}{\sqrt{\varepsilon}} . \quad (7)$$

With regard of the expression (5) we obtain

https://doi.org/10.32933/ActaInnovations.36.6• ISSN 2300-5599 •

$$E = \sqrt{\frac{P}{\varepsilon_0 c S \sqrt{\varepsilon}}}\ . \tag{8}$$

Thus, formula (8) takes into account interrelation between microwave generator power and magnitude of electromagnetic field on the surface of a food product.
For calculation of magnitude of electromagnetic field according to the thickness of a product, we use formula

$$E_\Delta = E \cdot \exp\left(-\frac{\Delta}{\delta}\right), \tag{9}$$

where E_Δ is the magnitude of electromagnetic field on the distance Δ from surface of product, m.

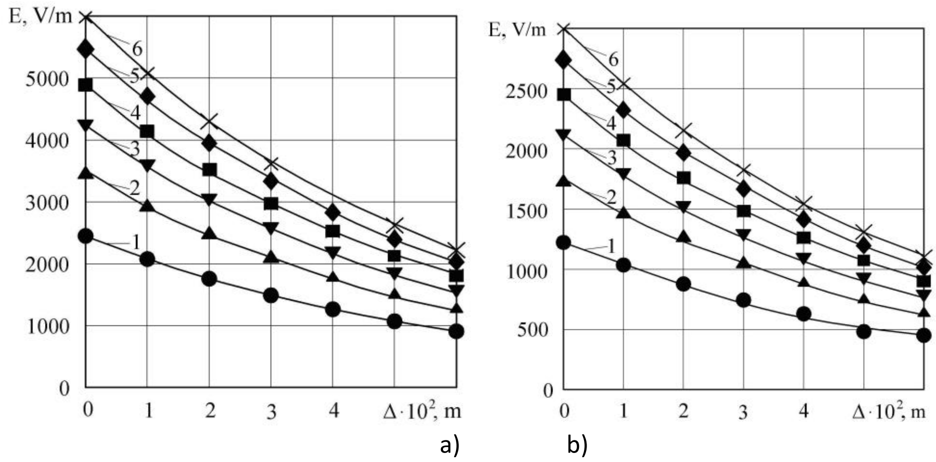
$$\delta = \frac{c\sqrt{\varepsilon}}{\pi f \varepsilon''} \tag{10}$$

δ is the penetration depth of electromagnetic field into the dielectric material, m.

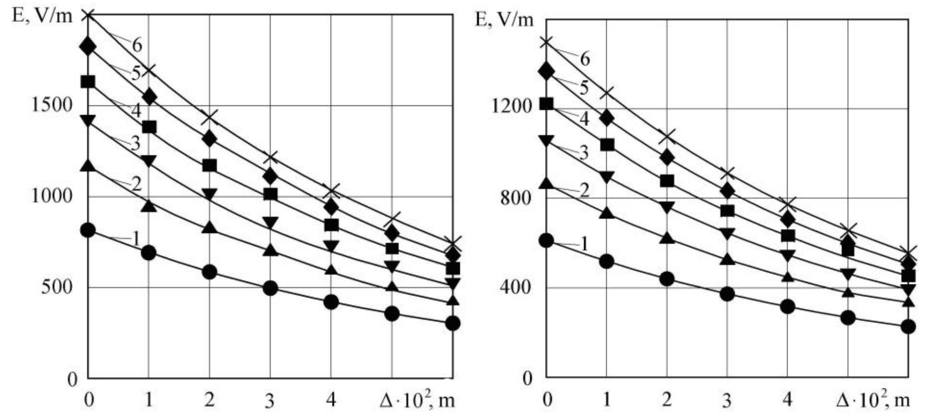
Substituting in formula (9) expressions for E (8) and δ (10), we obtain a formula for calculating the strength of the electromagnetic field depending on the thickness of the product, its surface area and microwave power.

$$E_\Delta = \sqrt{\frac{P}{\varepsilon_0 \sqrt{\varepsilon} c S}} \cdot \exp\left(-\frac{\pi f \varepsilon'' \Delta}{c\sqrt{\varepsilon}}\right), \tag{11}$$

We used formula (11) to calculate the dependences of the magnitude electromagnetic field on the power of the microwave generator and the surface area of the product, depending on the layer thickness of two products: 1 - a mixture of finely chopped root vegetables of spicy vegetables (Figure 1); 2 - a mixture of finely chopped herbs of spicy vegetables (Fig. 2) [10].

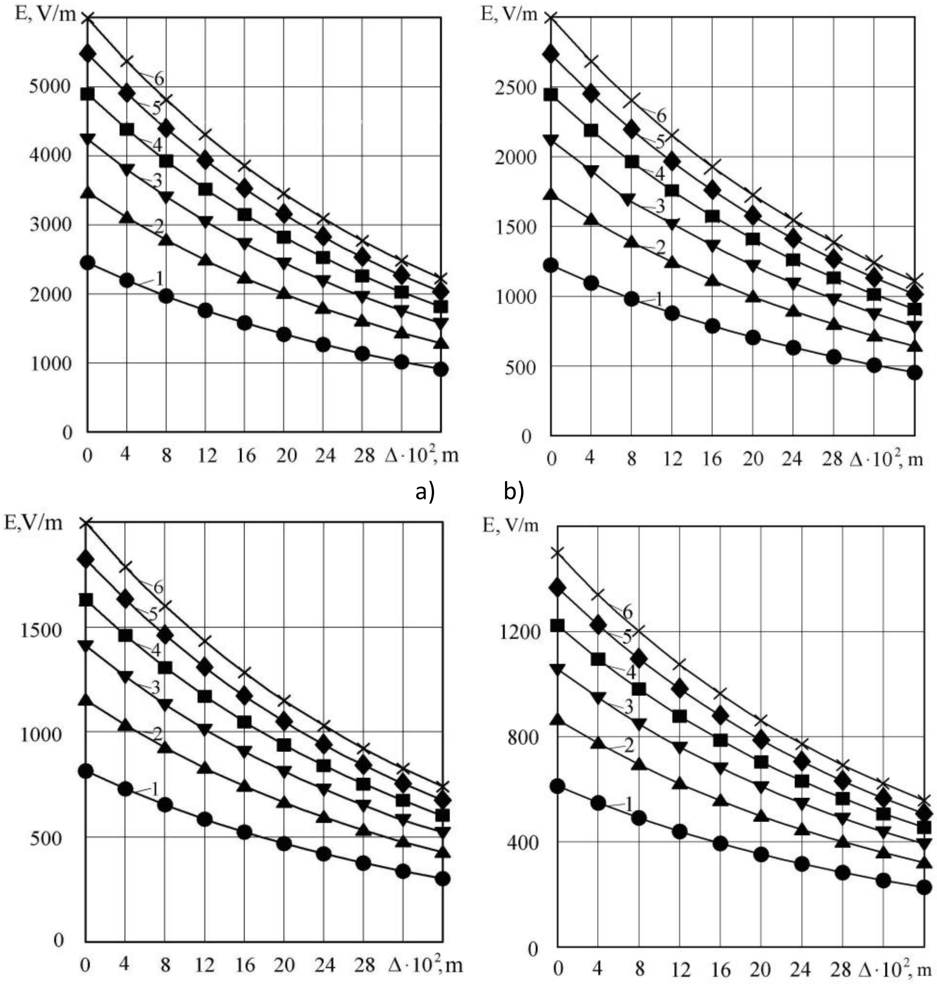


a) b)



c) d)

Fig. 1. Magnitude of strength of electromagnetic field depending on the thickness of the layer (Δ) and microwave power (*P*) for mixture of finely-chopped roots of spicy vegetables: 1 – 500 W; 2 – 1000 W; 3 – 1500 W; 4 – 2000 W; 5 – 2500 W; 6 – 3000 W, for surface area of a product: a – 50 cm2; b – 200 cm2; c – 450 cm2; d – 800 cm2.



c) d)

Fig 2. Magnitude of strength of electromagnetic field depending on the thickness of the layer (Δ) and microwave power (*P*) for mixture of finely-chopped greenery of spicy vegetables: 1 – 500 W; 2 – 1000 W; 3 – 1500 W; 4 – 2000 W; 5 – 2500 W; 6 – 3000 W, for surface area of a product: a – 200 cm2; b – 800 cm2; c – 1800 cm2; d – 3200 cm2

According to the data of (Figure 1, Figure 2) it can be seen that with the increase of microwave generator power within the above mentioned range from 500 W to 3000 W electromagnetic field strength increases approximately by 2 times in all cases. Magnitude of electromagnetic field strength into the product is inversely to the surface area of a product.
Hence, by this example of calculations it was shown that electromagnetic field strength can be regulated through the change of microwave power and surface area of the product.
Since the intensity of internal heat sources arising during microwave heating depends on the square of the strength of the electromagnetic field (1) penetrating into the product, the proposed formula (11) allows to choose the rational characteristics of the microwave heating process, that is, regulate the radiation power, surface areas and the thickness of the product.

Comparison of sensory quality of conventionally treated nuts and microwaved nuts
Sensory quality evaluation

The interest in sensory evaluation grew rapidly in the second half of the 20th century, which is related to the development of industry, the appearance of processed foods and consumer products. The first initiation of formal quality control or sensory programs by use of trained panels dates to 1950 [11], [12]. Sensory evaluation
The interest in sensory evaluation grew rapidly in the second half of the 20th century, which is related to the development of industry, the appearance of processed foods and consumer products. The first initiation of formal quality control or sensory programs by use of trained panels dates to 1950 [11], [12]. Sensory evaluation involves a suite of techniques to accurately measure human responses to food and minimizes the potentially biased effects of brand identity and other information affecting consumer perception.
As such, it tries to isolate the sensory properties of the food itself and provides important and useful information about the product to developers, food scientists, and managers about the sensory qualities of their products.
One of the most complex, dynamically developing and frequently used methods of sensory analysis is Quantitative Descriptive Analysis (QDA) [13], [14]. This method, also known as the profiling method, is used for the qualitative and quantitative determination of the comprehensive characteristics of food products. Its basic assumption is that the palatability, smell or texture are not individual product quality features, but a complex of many individual features that can be distinguished, identified and defined. A special preliminary procedure allows selecting the characteristic units of the analysed products and establishing their definitions. The profile analysis may be complete, i.e. it may concern discriminants perceived through all senses (sight, smell, taste and sensory and tactile senses) or partial, including only smell and taste features or texture features. Each feature is quantified on a linear (or numerical) scale with appropriate boundary definitions. The results of the assessment are converted into numerical values and then subjected to statistical processing, using the analysis of variance (ANOVA) to determine which of the characteristics significantly differentiate the tested samples and whether the repeated assessments (separate sessions) are not a significant factor of variation.

Thermal processing of nuts
One of the most important processing methods of dried nuts is roasting. It significantly increases the sensory qualities of nuts, especially the palatability, by enhancing the taste, colour and increasing crunchiness [15], [16]. Roasted nuts can be eaten without any additives as popular snacks “on the go”, they constitute material in confectionery, bakery and others. The most often roasted are peanuts, hazelnuts, almonds and pistachio nuts [17]. Roasting the nuts involves heat treatment (e.g. with hot air or infrared) at a temperature of 104-300 °C, for time depending on the type of nuts and desired properties [15], [16]. Hot air roasting is one of the simplest and low-cost methods. However, it usually requires a long period of roasting time which results in undesirable changes in the final product, mainly due to the Maillard reaction [16], [18]. In conventional roasting methods, the outer surface of the nut is scorched while the centre of the nut is not perfectly baked. This may cause uneven roasting, surface scorching, unpleasant odours and a bitter-burnt taste. To overcome uneven roasting and its disadvantages, new methods such as infrared heating can improve roasting properties. New mild food processing technologies that use low temperatures and limited amounts of processing aids can facilitate preservation of nutrients, maintain good nutritional quality and bioavailability, extend product shelf life, optimize individual ingredients and maximize functional properties (technological functions, sensory attributes, nutritional value) [15], [19], [20]. One of that technology is microwave roasting. This process assures lower processing time by a significantly reduced temperature. Interaction of an electromagnetic field with chemical components of food

https://doi.org/10.32933/ActaInnovations.36.6• ISSN 2300-5599 •

causes a heating of food products. These interactions immediately generate heat due to molecular friction andexcitation [21]. In the present study we are comparing two methods (microwave and convection) of roasting nuts (peanuts, hazelnuts, walnuts), we considered on the sensory evaluation and environmental impact of roasting.

Materials and methods

Raw shelled nuts (peanuts, hazelnuts, walnuts) were split into batches. The first batch of nuts was exposed to microwave radiation for 4, 6 and 8 minutes, using microwave power of 500, 600 and 800 W (Table 1). Each sample (200 g) was placed in a turn vessel, roasted, and then cooled. The microwave radiation treatment was carried out using a microwave oven under constant air pressure. The average temperature of a sample immediately after roasting was 75 °C. The second batch was dry roasted at a temperature of 180 °C for 5, 15, 20 and 25 minutes (WINKLER kiln) (Table 1). After cooling to ambient temperature, seeds were sealed in a protective atmosphere (N2 according to EC Directive 1272/2008 [22]) and stored at 20 °C prior to processing.

Sensory properties of nuts were tested by means of Quantitative Descriptive Analysis (QDA) by a trained panel. The panel (15 assessors chosen by means of a suitability test and trained for the evaluation of seeds) drew up a sensory profile of products with the following characteristics: odour (total odour intensity – total strength of all odours in the sample; characteristic odour – typical for nuts; foreign odour – atypical for nuts), colour and size (typical for nuts), hardness (sample resistance on biting and crispness – susceptibility to cracking under the pressure of teeth), taste (sour – basic flavour; foreign – atypical for nuts). The intensity evaluation of the sensory perception by the trained panel was carried out by use of unstructured scales (0 – not perceptible and 100 – strongly perceptible). Moreover, the degree of consumer preference was determined. The trained panel worked in a laboratory under defined conditions. The results were captured with the MySurveyLab software.

The environmental impact of roasting methods was determined using the LCA analysis. The study was conducted in the OpenLCA software, using the ELCD 3.2 database. To assess the impact of the processes on the environment, the ReCiPe Endpoint (E, A) method was used, which allowed to obtain harmonized results and compare nuts in terms of their impact on various elements of the environment. As the input data, we took into account only theses parameters by which roasting methods differ from each other, i.e. energy consumption and exhaust emissions. The analysis was performed only for these nuts that have been assessed of having the most favourable sensory parameters.

Table 1. Roasting conditions for nuts

Roasting	**Convection**				**Microwave**									
temperature [°C]	180	180	180	180	**power [W]**	500	500	500	600	600	600	800	800	800
time (min)	5	15	20	25	**time (min)**	4	6	8	4	6	8	4	6	8
peanuts symbol	AK5	AK15	AK20	AK25	**peanuts symbol**	AM54	AM56	AM58	AM64	AM66	AM68	AM84	AM86	AM88
hazelnuts symbol	LK5	LK15	LK20	LK25	**hazelnuts symbol**	LM54	LM56	LM58	LM64	LM66	LM68	LM84	LM86	LM88
walnuts symbol	WK5	WK15	WK20	WK25	**walnuts symbol**	WM54	WM56	WM58	WM64	WM66	WM68	WM 84	WM86	WM 88

Result and discussion

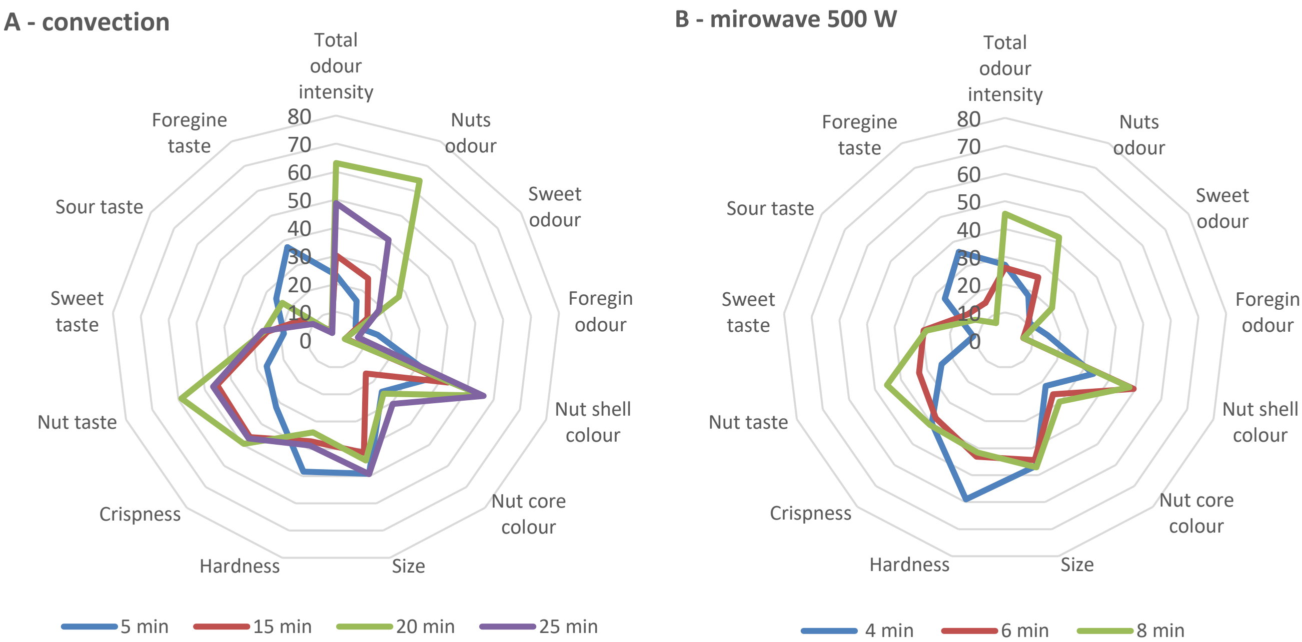
<u>Peanuts</u>

Statistical analysis of the results showed significant differences in overall odour intensity and nutty flavour in conventionally roasted samples. After roasting for 20 minutes, higher scores for these parameters were recorded. Moreover, the nutty taste of these samples (AK20) was rated higher than those of the samples roasted for 5, 15 and 25 minutes (Figure 3, A). The degree of consumer acceptance and overall product desirability for peanuts roasted for 5 minutes was significantly lower.

In the case of microwave-roasted samples, significant differences were observed in the overall intensity of the nutty odour and total odour as well as the nutty and sweet taste. The highest values of these parameters were

https://doi.org/10.32933/ActaInnovations.36.6• ISSN 2300-5599 •

determined in samples processed for 6 minutes, 800 W (Figure 3, D, E). These samples (AM86) were rated the best by the panel of experts. According to the evaluators, extending the roasting time reduces the hardness of microwave roasted peanuts. Similar, Jindal et al. study shows that the sensory crispness score based on the overall acceptability of roasted peanuts appeared to increase at first with an increase in power level and roasting time, and then showing a decrease due to excessive roasting [23]. On the other hand, the degree of consumer acceptance and the general desirability of the product for samples roasted at 800 W were rated significantly better than peanuts roasted at 500 W and 600 W. The worst grades were those roasted for 4 minutes, 500 W. Similar results were obtained in the publication Raigar et al., in this study, the microwave roasting of peanuts was attempted, optimized and compared with conventional drum roasting. Overall acceptability of microwave roasted peanuts increased with power levels. The observed trend can be explained by the increase in the formation of flavour qualities and Maillard serial roasting tests, which include the overall sensory quality of peanuts. The optimal overall acceptability was obtained with roasting time 201 s and power 898 W [24]. On the other hand, peanuts which were heated as part of the blanching process using a 5 kW, 915 MHz microwave unit in comparison to roast samples at 177 °C were significantly higher in total off note, which is a term encompassing all negative aspects of the sample that are different from a reference. The microwave-blanched peanuts also displayed higher intensities of dark/ashy, bitter, and cardboard/stale notes, which also may contribute in part to the total offnote score. The microwave and lowest temperature oven roast had the highest level of dark roast attribute, which may be explained by the unevenness of the microwave roasting and long roasting time in the oven, respectively [25].



https://doi.org/10.32933/ActaInnovations.36.6• ISSN 2300-5599 •

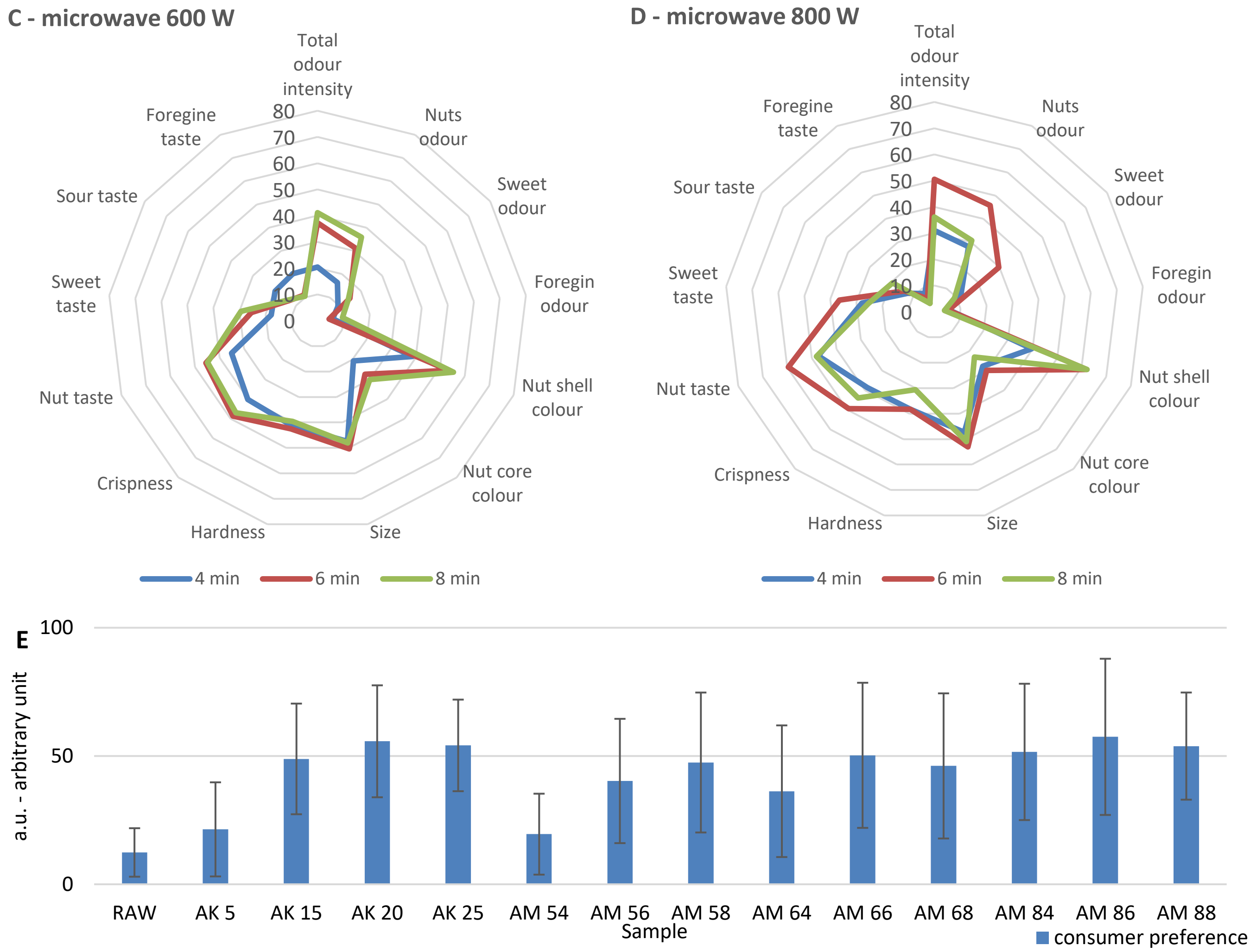


Fig. 3 Sensory profile of peanuts roasting by use of convection (A), microwave - power 500 W (B), microwave - power 600 W (C), microwave - power 800 W (D) and consumer preference of peanuts (E); (a.u. – arbitrary unit)

Hazelnuts

Based on the results obtained for the conventionally roasted samples, it was found that the roasting time of 20 minutes (LK20) was the most favourable according to the evaluators. These samples had higher ratings for the degree of consumer acceptance (Figure 4, E), and were also characterized by lower hardness (Figure 4, A). Hazelnuts roasted conventionally for 5 minutes had a higher hardness rate. In addition, the evaluators found them more bitter than those conventionally roasted for a longer time. Roasting the hazelnuts for 25 minutes caused the shell and core of the samples to turn darker. Extending the conventional roasting time increased brittleness of the tested nuts.

The statistical analyses performed showed a homogeneity of all groups of microwave-roasted samples, except for the discriminants characterizing the colour. The samples processed at the power of 800 W were characterized by a darker colour of the shell and core (Figure 4, D). On the other hand, Donno et al. study shows that roasting temperature is the most important factor affecting the nut quality indicators and the descriptor that varied the most among samples is hazelnut odour [26]. The team Belvisio at al. made similar observations about temperature of roasting. Significant sensory differences occur only when the roasting temperature was high, and this difference persisted during storage [27].

In comments, the evaluators described microwave-roasted hazelnuts as "typical for good-quality chocolates with nuts". Ciarmiello et al. studies compared microwave-roasted hazelnuts treated with exposures times of 240, 300, 360, 450 and 600 s (microwave frequency of 2.45 GHz) with conventional oven treatment of 20 min at 120 °C indicated that the best taste score was recorded with 450 s and 600 s microwave treatment [28].

https://doi.org/10.32933/ActaInnovations.36.6• ISSN 2300-5599 •

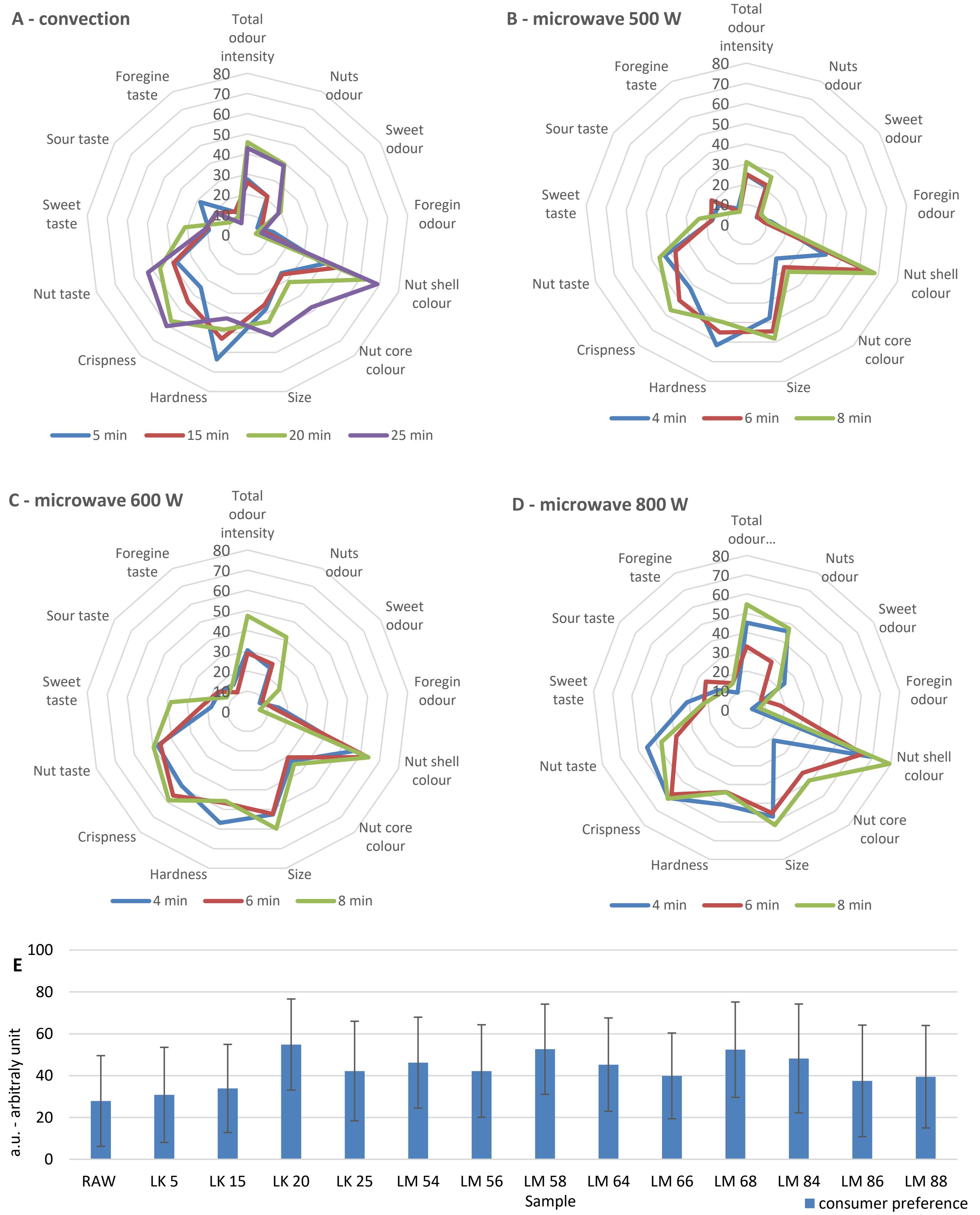


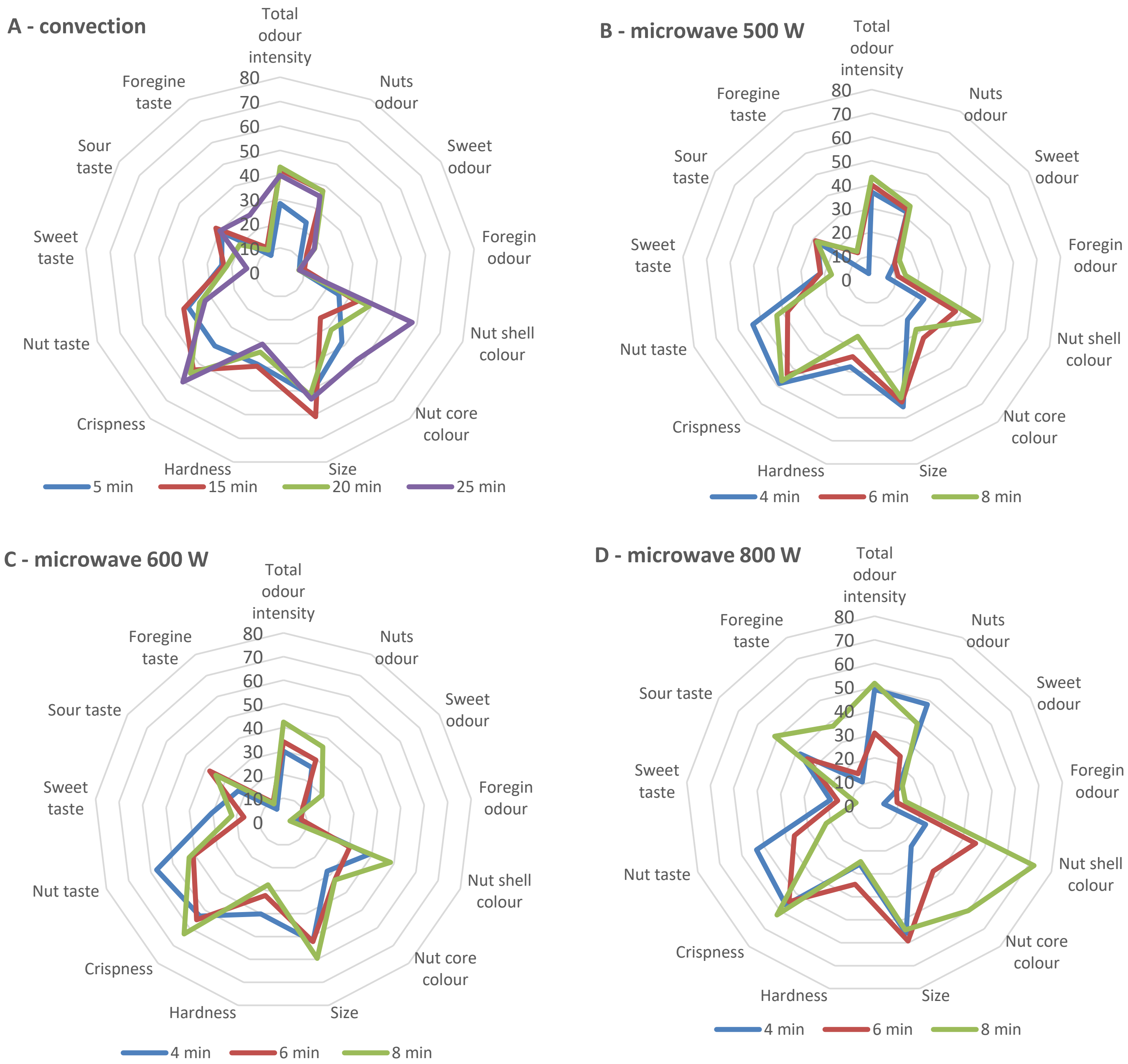
Fig. 4. Sensory profile of hazelnuts roasting by use of convection (A), microwave - power 500 W (B), microwave - power 600 W (C), microwave - power 800 W (D) and consumer preference of hazelnuts (E); (a.u. – arbitrary unit)

https://doi.org/10.32933/ActaInnovations.36.6• ISSN 2300-5599 •

Walnuts

In assessing the degree of consumer acceptance, samples of walnut conventionally roasted for 15 minutes (WK15) were rated as better. Conventional roasting of the samples for 25 minutes caused the shell and core to turn darker (Figure 5, A). Along with the extension of the roasting time from 5 to 25 minutes, an increase in the perception of foreign taste was observed. These observations are confirmed by the studies of Kita et al., it was observed that with increasing temperature and roasting time, nuts became more and more bitter, and their taste can be described as strange and unpleasant [17].

The analysis of the results of expert evaluation of microwave-roasted walnuts showed that the most favourable sensory properties were those of the samples roasted for 4 minutes, 600 W (Figure 5, E). According to the expert panel, these samples (WM64) were sweeter and had a more perceptible nut flavour (Figure 5, C). Moreover, in assessing the degree of consumer acceptance and general desirability of the product, samples of microwave-roasted walnut (600 W, 4 minutes) were characterized by higher scores. Worse assessments of the sensory evaluation factors were observed in case of walnuts samples roasted with microwaves at the power of 800 W for 8 minutes (Figure 5, D). For all tested kind of nuts, there were none statistically significant differences between judges regarding sensory attributes observed.



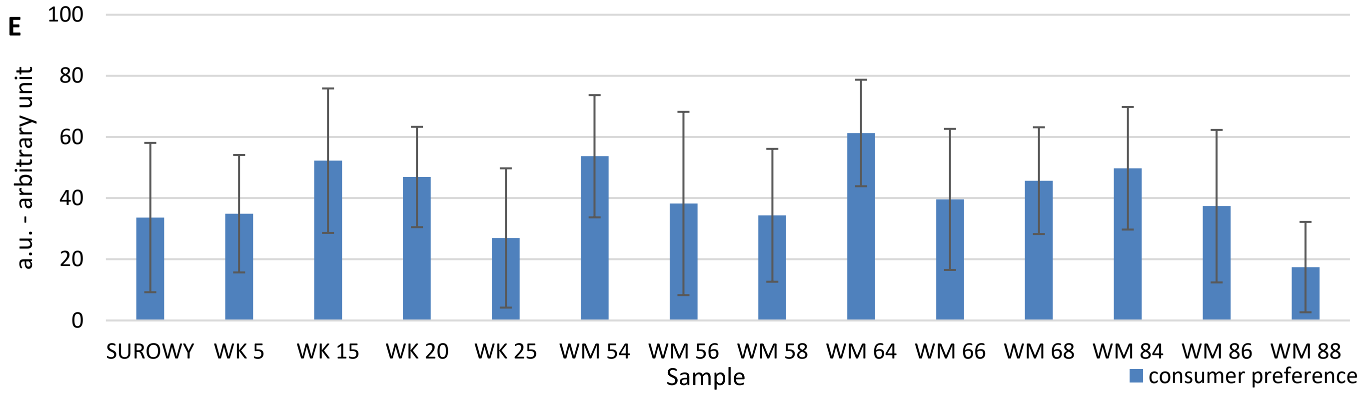


Fig. 5 Sensory profile of walnuts roasting by use of convection (A), microwave - power 500 W (B), microwave - power 600 W (C), microwave - power 800 W (D) and consumer preference of walnuts (E); (a.u. – arbitrary unit)

Environmental impact of roasting methods

The demand for energy in the microwave roasting process is higher than in the conventional roasting for all of the tested nuts (Table 2). The smallest difference was observed for walnuts (~ 14 times) and the largest for hazelnuts (~ 21 times). The disadvantage of convectional roasting is the emission of greenhouse gases resulting from the combustion of butane, which is used to power traditional kilns. In the case of microwave devices, which are powered entirely by electricity, there are no direct exhaust gases emissions. Due to the fact that neither process generates waste nor requires the use of water, convectional and microwave roasting are equivalent in this respect.

Table 2. Energy consumption and CO2 emissions related to roasting seeds and nuts with various methods

Symbol	Nuts	Roasting method	Electricity consumption [kWh/kg nuts]	Buthane consumption [kWh/kg nuts]	Exhaust emissions [kg CO_2/ kg nuts]
WM64	walnuts	microwave	6.2096	0	0
LM68	hazelnuts	microwave	12.4316	0	0
AM86	peanuts	microwave	9.3075	0	0
WK15	walnuts	convection	0	0.4339	0.0957
LK20	hazelnuts	convection	0	0.5786	0.1276
AK20	peanuts	convection	0	0.5786	0.1276

To analyse other environmental impacts, not only energy consumption and direct emissions, we performed the LCA analysis for three variants: convectional roasting in a butane-powered kiln, microwave roasting powered by electricity from the Polish power grid, and microwave roasting powered by energy from renewable energy sources (RES). For each of the materials, microwave roasting powered by the power grid is the least favourable. The total environmental impact is from ~ 11 (walnut) to ~ 16 times (hazelnut) higher than convectional roasting (Figure 6). However, when switching from a national power grid to RES, the microwave roasting has significantly smaller impact on the environment - it is one order of magnitude smaller than for convectional roasting and two orders of magnitude smaller than for microwave roasting using energy from the power grid (Figure 6).

https://doi.org/10.32933/ActaInnovations.36.6• ISSN 2300-5599 •

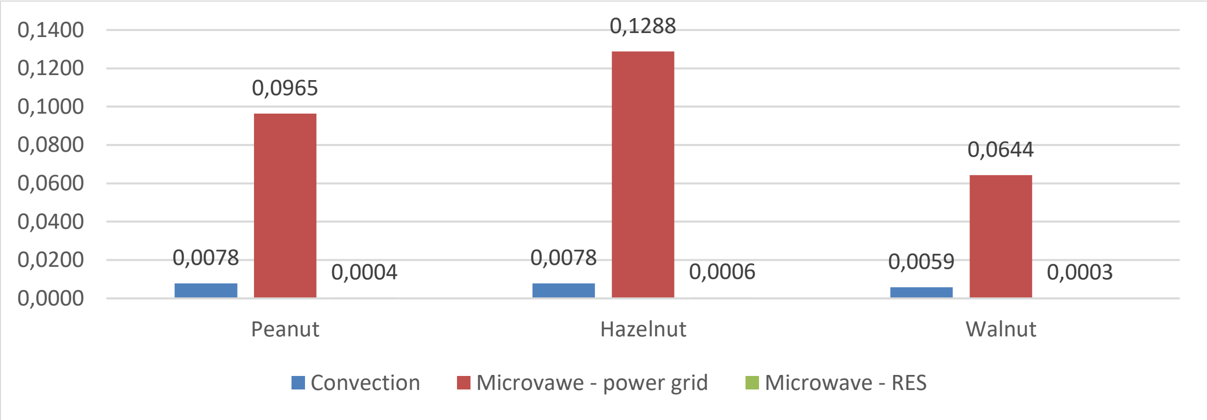


Fig. 6. Total environmental impact of roasting methods of nuts [points / kg of raw nuts]

Regardless of the nut type, the convectional roasting and microwave roasting powered with RES contribute to a smaller number of categories than microwave roasting (Table 3). Out of 17 impact categories, conventional and microwave roasting from RES have an impact on climate change, and thus on ecosystems and health. Microwave roasting powered from the power grid affects 9 additional categories, including human toxicity. This is mainly due to the structure of electricity production in Poland, based in over 80% on hard coal and lignite, and related toxic pollutions emitted by power stations [29]. On the other hand, all roasting methods are resource-neutral.

Table 3. Impact of the roasting methods of raw nuts on the environment by categories (green - no impact; red - maximum observed impact)

Impact category	AK20	AM86_grid	AM86_RES	LK20	LM68_grid	LM68_RES	WK15	WM64_grid	WM64_RES
ecosystem quality (agricultural land occupation)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ecosystem quality (climate change, ecosystems)	0.0035	0.0008	0.0000	0.0035	0.0011	0.0001	0.0026	0.0006	0.0000
ecosystem quality (freshwater ecotoxicity)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ecosystem quality (freshwater eutrophication)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ecosystem quality (marine ecotoxicity)	0.0000	0.0008	0.0000	0.0000	0.0011	0.0000	0.0000	0.0006	0.0000
ecosystem quality (natural land transformation)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ecosystem quality (terrestrial acidification)	0.0000	0.0006	0.0000	0.0000	0.0008	0.0000	0.0000	0.0004	0.0000
ecosystem quality (terrestrial ecotoxicity)	0.0000	0.0001	0.0000	0.0000	0.0002	0.0000	0.0000	0.0001	0.0000
ecosystem quality (urban land occupation)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
human health (climate change, human health)	0.0044	0.0011	0.0000	0.0044	0.0014	0.0001	0.0033	0.0007	0.0000
human health (human toxicity)	0.0000	0.0754	0.0001	0.0000	0.1007	0.0002	0.0000	0.0503	0.0001
human health (ionising radiation)	0.0000	0.0001	0.0000	0.0000	0.0002	0.0000	0.0000	0.0001	0.0000
human health (ozone depletion)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
human health (particulate matter formation)	0.0000	0.0175	0.0002	0.0000	0.0233	0.0002	0.0000	0.0117	0.0001
human health (photochemical oxidant formation)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
resources (fossil depletion)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
resources (metal depletion)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ecosystem quality (total)	0.0035	0.0023	0.0000	0.0035	0.0032	0.0001	0.0026	0.0017	0.0000
human health (total)	0.0044	0.0941	0.0003	0.0044	0.1256	0.0005	0.0033	0.0628	0.0002
resources (total)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
total	0.0079	0.0964	0.0003	0.0079	0.1288	0.0006	0.0059	0.0645	0.0002

Impact

Replacing conventional roasting technologies with microwave methods results in a significant, positive technological, environmental and economic impact.

Technological impact

New, gentle methods of processing dried fruits and nuts are based on the reduction of processing time and temperature needed to carry out the process. The lower temperature may limit the formation of Maillard compounds above 140 °C. However, the microwave roasting is more energy-intensive/ consuming than conventional roasting. Nevertheless, thanks to using renewable energy sources, the impact on the environment may be 14 ÷ 28 times lower than conventional roasting (depending on the raw material) and 231 times less than microwave roasting powered from the power grid. Thus, the introduction of microwave technologies in the food industry causes the technological snowball effect - prompts and stimulates to search for new technological solutions that enable lower energy costs.

Economic impact

Shortening the roasting time thanks to microwave technologies can impact on the economic aspects. Shorter roasting time increases productivity while maintaining high quality products.

Environmental impact

Traditional roasting processes use fossil fuels, most often natural gas, to power bakery ovens. Therefore, the emission of greenhouse gases resulting from the combustion of gas (butane) is undesirable for the natural environment. The introduction of integrated technological solutions - microwave roasting of dried fruits and nuts, powered by RES energy [30], will have a positive impact on environmental issues. Due to the drive to increase the share of energy from renewable sources related to EU policy, the use of microwave roasting installations in the factory will have a positive impact on environmental issues.

Conclusions

The results of microwave processing depend on the generation of microwave energy, its transfer through the media, penetration into the product and conversion into heat. The proposed physical model allows to choose the rational characteristics of the microwave heating process, that is, regulate the radiation power, surface areas and the thickness of the product. Data available to date indicate that roasting with the use of microwaves positively influences on properties of food. Convection roasting is a proven and frequently used method of processing dried fruits and nuts, while microwave roasting has never been used on a large scale. The type of roasting method affects the sensory properties of peanuts, hazelnuts and walnuts. Evaluation of unroasted, microwave and convectional roasted samples showed that convection roasting had increased intensity of the smell and taste. Microwave roasting did not diminish the sensory quality of the product expressed in general consumer preferences. The highest rated peanuts, roasted with microwaves, had the highest notes of nutty and sweet taste. On the other hand, according to experts' comments, microwave-roasted hazelnuts have been described as similar to nuts made of high-quality hazelnut chocolate, which is a positive feature. In the case of walnuts, microwave roasting significantly increased the overall acceptance of microwave-roasted nuts for 4 minutes at 600 W, they were rated as tastier and sweeter. There were none statistically significant differences between judges regarding sensory attributes observed. Furthermore, microwave roasting powered from RES has significantly lower environmental impact than convectional roasting.

Conflict of Interest

There are no conflicts to declare.

Acknowledgements

The article has been prepared within the Project “Development of improved food products with enhanced nutritional value as well as an unconventional heat treatment method” funded by the "Cooperation" measure covered by the Rural Development Program for 2014-2020, co-financed by the European Union under the European Agricultural Fund for Rural Development, based on the grant agreement No. 00007.DDD.6509.00013.2017.05. “European Agricultural Fund for Rural Development: Europe investing in rural areas”.

References

[1] Ververis E, Ackerl, R, Azollini D, Colombo PA, da Sesmaisons A, Dumas C, Fernandez-Dumont A, Ferreira da Costa L, Germini A, Goumperis T, Kouloura E, Matijevic L, Precup G, Roldan-Torres R, Rossi A, Svejstil R, Turla E, Gelbmann W. Novel foods in the European Union: Scientific requirements and challenges of the risk assessment process by the European Food Safety Authority. Food Reserch International 137 (2020), 109515.

[2] Statista, Value of global nuts and seeds market 2017-2024 - Statistic, 2017.

[3] Market Research Future Packaging (Jars and others) by Distribution Channel and Region (North America, Europe, Asia-Pacific and RoW) - Forecast period from 2018 to 2023. Maharashtra, India, 2020.

[4] Singh-Ackbarali D, Maharaj R. Sensory Evaluation as a Tool in Determining Acceptability of Innovative Products Developed by Undergraduate Students in Food Science and Technology at The University of Trinidad and Tobago. Journal of Curriculum and Teaching 3 (2014), 1.

[5] GVR. Healthy Snacks Market Size, Share - Industry Growth Report, 2019-2025. Grand View Research (2019).

[6] KPMG. Rynek słodyczy w Polsce. Warszawa (2014).
[7] Chalyi S, Levykin I, Guryev I. Model and technology for prioritizing the implementation end-to-end business processes components of the green economy. Acta Innovations 35 (2020), 65–80.
[8] Ratajczyk F. Director of Innovations Development Department Bakalland SA (2020).
[9] Metaxas AC. Foundation and Electroheat: A Unified Approach. John Wiley & Sons Ltd., (1996).
[10] Potapov VO, Mykhailov VM, Mykhailova SV, Borisova AO. Substantiation of a Physical Model of Electromagnetic Field Interaction with a Food Product of an Arbitrary Form. Acta Mechanica Slovaca 17 (2013), 78–83.
[11] Lawless HT, Heymann H. Sensory Evaluation of Food, Springer (2012).
[12] Muñoz AM. Sensory evaluation in quality control: An overview, new developments and future opportunities. Food Quality and Preference 13 (2002), 329–339.
[13] Sidel JL, Bleibaum RN, Tao KWWC. Quantitative Descriptive Analysis, in Kemp SE, Hort J, Hollowood T (Eds.) Descriptive Analysis in Sensory Evaluation. Chichester, UK: John Wiley & Sons, Ltd (2017), 287–318.
[14] Kemp SE, Hort J, Hollowood T. Descriptive Analysis in Sensory Evaluation. Chichester, UK: John Wiley & Sons, Ltd (2017).
[15] Perren R, Escher FE. Impact of roasting on nut quality. Woodhead Publishing Limited (2013).
[16] Schlörmann W, Birringer M, Bohm V, Lober K, Jahreis G, Lorkowski S, Muller AK, Schone F, Glei M. Influence of roasting conditions on health-related compounds in different nuts. Food Chemistry 180 (2015), 77–85.
[17] Kita A, Figiel A. The effect of roasting on the texture of walnuts. Acta Agrophysica 7 (2006), 89–94.
[18] Açar ÖC, Gökmen V, Pellegrini N, Fogliano V. Direct evaluation of the total antioxidant capacity of raw and roasted pulses, nuts and seeds, European Food Research and Technology 229 (2009), 961–969.
[19] Goszkiewicz A, Kołodziejczyk E, Ratajczyk F. Comparison of microwave and convection method of roasting sunflower seeds and its effect on sensory quality, texture and physicochemical characteristics. Food Structure 25 (2020), 100144.
[20] Al Juhaimi F, Özcan MM, Uslu N, Doğu S. Pecan walnut (Carya illinoinensis (Wangenh.) K. Koch) oil quality and phenolic compounds as affected by microwave and conventional roasting. Journal of Food Science and Technology 54 (2017), 4436–4441.
[21] Sun J, Wang W, Yue Q. Review on microwave-matter interaction fundamentals and efficient microwave-associated heating strategies. Materials 9 (2016), 231.
[22] Regulation (EC) no 1272/2008 of the European Parliament and of the Council. Official Journal of the European Union (2008) L 353.
[23] Jindal VK, Anjinta A, Koolvisoot P. Optimization of Microwave Oven Roasting of Peanuts Using Response Surface Methodology. Journal of Food Science and Technology 54 (2017), 2145-2155.
[24] Raigar RK, Upadhyay R, Mishra HN. Optimization of microwave roasting of peanuts and evaluation of its physicochemical and sensory attributes. Journal of Food Science and Technology 54 (2017), 2145–2155.
[25] Smith AL, Perry JJ, Marshall JA, Yousef AE, Barringer SA. Oven, Microwave, and Combination Roasting of Peanuts: Comparison of Inactivation of Salmonella Surrogate Enterococcus faecium , Color, Volatiles, Flavor, and Lipid Oxidation. Journal of Food Science 79 (2014), S1584–S1594.
[26] Donno D, Beccaro GL, Mellano GM, Di Prima S, Cavicchioli M, Cerutti AK, Bounous G. Setting a Protocol for Hazelnut Roasting using Sensory and Colorimetric Analysis: Influence of the Roasting Temperature on the Quality of Tonda Gentile delle Langhe Cv. Hazelnut. Czech Journal of Food Science 31 (2013), 390-400.
[27] Belviso S, Dal Bello B, Giacosa S, Berolino M, Ghirardello D, Giordano M, Rolle L, Gerbi V, Zeppa G. Chemical, mechanical and sensory monitoring of hot air- and infrared-roasted hazelnuts (Corylus avellana L.) during nine months of storage', Food Chemistry 217 (2017), 398–408.
[28] Ciarmiello L, Piccirillo P, Gerardi C, Piro F, Luca A, D'Imperio F, Rosito V, Poltonieri P, Santino A. Microwave Irradiation for Dry-Roasting of Hazelnuts and Evaluation of Microwave Treatment on Hazelnuts Peeling and Fatty Acid Oxidation. Journal of Food Research 2 (2013), 3.
[29] Czajkowska A. The changes in the Polish energy sector to reduce the pollutant emissions in the environment. Acta Innovations 30 (2019), 85–95.
[30] Anduła A, Heim D. Photovoltaic systems – types of installations, materials, monitoring and modeling - review. Acta Innovations 34 (2020) 40–49.