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EURECA-PRO

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SUSTAINABLE PRODUCTION AND CONSUMPTION

SELECTED ENVIRONMENTAL ASPECTS

WYDAWNICTWO POLITECHNIKI ŚLĄSKIEJ

GLIWICE 2023

MONOGRAFIA

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SPIS TREŚCI

1. INTRODUCTION

In today's rapidly changing world, the concept of sustainable consumption and production has emerged as a critical issue. As we strive for a more sustainable future, it is essential to address the challenges associated with our consumption patterns and production processes. This monograph aims to delve into the multifaceted aspects of sustainability, focusing on various key areas such as air quality, water resources, waste management, energy and soil conservation.

The United Nations' Sustainable Development Goals (SDGs) provide a framework for global action, and among these goals, Goal 12 stands out as a significant milestone. Goal 12 specifically targets sustainable consumption and production, urging us to adopt responsible practices that minimise waste generation, promote resource efficiency and reduce the ecological footprint of our activities. This monograph aims to contribute to the realisation of this goal by exploring the intricate relationship between consumption, production and sustainability.

Within the realm of soil, we explore the importance of its sustainable use and fertilisation. Soil is not merely a medium for plant growth; it is a vital environmental component that supports biodiversity and performs a crucial role in various ecosystem services. By examining soil management practices, first chapter offers valuable insights into how we can ensure its long-term sustainability and promote responsible land use.

Water resources are another key aspect of sustainable consumption and production. The chapter dedicated to water addresses the pressing issue of water pollution by inorganic and organic compounds, as well as microplastics. Through a comprehensive analysis of these aspects, the chapter emphasises the urgent need for water conservation and effective measures of pollution control. It aims to raise awareness about the scarcity of water and its environmental implications, urging readers to take action to protect this precious resource.

The evolving role of sewage treatment plants as energy producers is the focus of the wastewater chapter. It delves into topics such as the removal and recovery of nitrogen, phosphorus and micropollutants, as well as introducing the intriguing concept of biorefineries. By exploring these topics, the chapter offers a comprehensive view of sustainable wastewater management, highlighting the potential for resource recovery and energy generation.

Waste management is a crucial aspect of sustainable consumption and production, and the corresponding chapter explores the principles of a sustainable waste management hierarchy, transformation methods and the principles of a circular economy. Additionally, it provides insights into sustainable production practices and responsible consumer behaviour, aiming to inspire individuals and communities to adopt more environmentally conscious habits.

The issue of air pollution is examined from two perspectives: outdoor and indoor air quality. The chapter on outdoor air pollution explores its impact on human health, highlighting the sources of pollution, air quality monitoring, and strategies to reduce air pollution, whereas the chapter on indoor air quality covers aspects of sustainable building practices, Indoor Environmental Quality (IEQ) standards, life cycle assessment (LCA) and building standardisation. Together, these chapters shed light on the importance of clean air and offer practical solutions for improving air quality.

Lastly, the monograph delves into the realm of energy, examining future energy technologies such as hydrogen and addressing the challenges of energy production within the context of prosumers. By exploring these interconnected aspects of sustainable production and consumption, this monograph aims to provide readers with valuable knowledge and insights. It encourages individuals and communities to take action towards a more sustainable future, aligned with the United Nations' goals for sustainable development.

In the pages that follow, we embark on a journey through the intricacies of sustainable consumption and production. By understanding the challenges and exploring potential solutions, we can collectively strive towards a more sustainable and resilient world. Let us embark on this transformative journey together, embracing our role as stewards of the planet and champions of sustainability.

2. SUSTAINABLE SOIL USE AND MANAGEMENT

Sustainable soil management (SSM) is an approach based on the persistent use of soil resources that balances environmental protection, soil use, and soil productivity. The preservation and improvement of soil quality in terms of SSM can be achieved by minimising erosion, maintaining the appropriate level of organic matter and nutrients, and ensuring optimal physical and chemical conditions for plant growth. This entails optimising the use of natural resources by minimising the use of water, energy and fossil fuels and improving the use of fertilisers [1]. The protection of biodiversity by minimising the use of pesticides and artificial fertilisers, increasing the diversity of crops and protecting natural habitats should also be taken into account. Sustainable soil management should consider the demands of local communities by ensuring adequate food quality, improving the living and working conditions of farmers, and protecting the cultural heritage related to agriculture [2].

The main assumptions of SSM are:

- Preservation and improvement of soil quality;
- Protection of biodiversity;
- Optimal use of natural resources;
- Waste minimisation;
- Supporting local communities.

To achieve the Sustainable Development Goals (SDGs) by the target date 2030, it is necessary to change how soils are used and managed. Research in the field of sustainable soil use and management should prioritise the multifunctional value of soil health and consider interdisciplinary linkages with such major issues as soil degradation, biodiversity, and climate change [3].

2.1. Soil related legal instruments and soil governance

There is a global soil database called SoiLEX, which aims to facilitate access to information on recommendations and legal instruments for protecting and preventing soil degradation. SoilLEX is a platform managed by the Global Soil Partnership within the FAO Land and Water Division together with FAOLEX. FAOLEX is one of the largest databases of legal acts and instruments related to the management of natural resources, food, and agriculture. The platform allows searching by country profiles or soil keywords. The database draws information from Statistical Offices of individual countries around the world. For example, information from Poland is provided by the Central Statistical Office. The catalogue of links to the websites of statistical offices in the countries around the world can be found on the website of the United Nations Department of Statistics [4].

In March 2022, the consultation of the EU Soil Strategy until 2030, presented at the end of 2020, ended. This strategy aims to rehabilitate all soils in Europe by 2050, increase their resilience, and provide them with adequate protection. Out of the seventeen sustainable development goals, soil management is included in eight of them (Fig. 2.1).

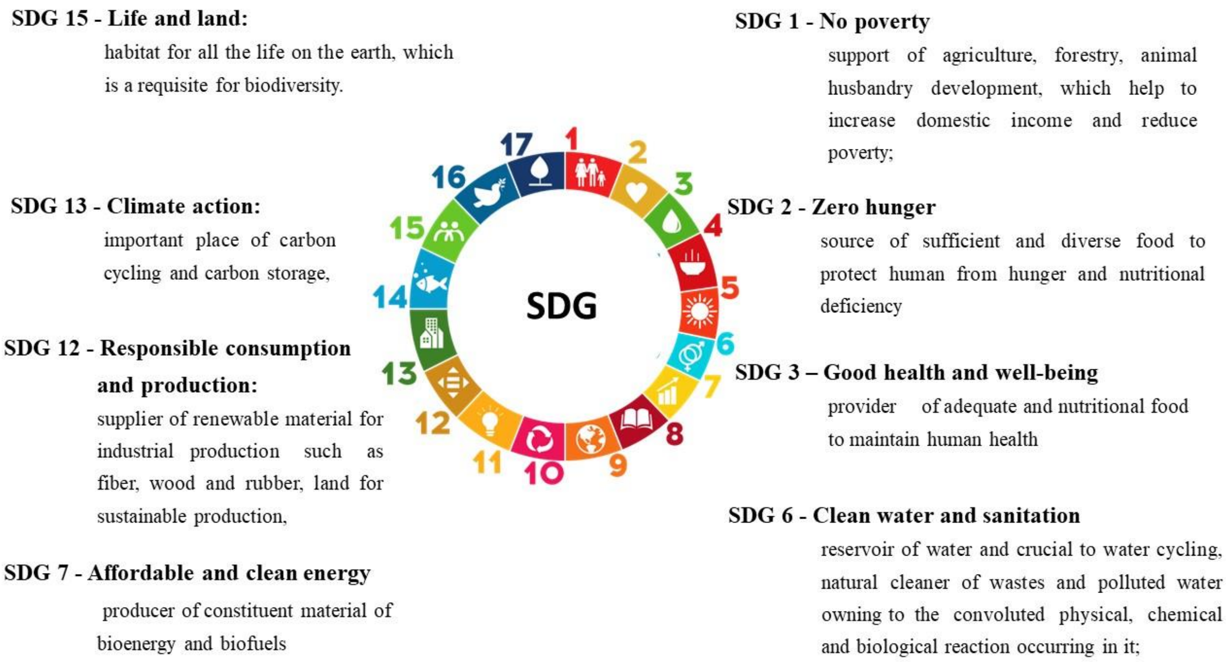

Fig. 2.1. Sustainable development goals for soil management [3]
Rys. 2.1. Cele zrównoważonego rozwoju w gospodarowaniu glebą [3]

The National Sustainable Agriculture Coalition (NSAC) is an alliance of grassroots organisations advocating for policy reform to enhance sustainable agriculture, food systems, natural resources, and rural communities. The NSAC's vision of agriculture is one in which safe, nutritious, abundant, and affordable food is produced by indigenous farmers who earn a decent living by selling their crops while protecting the environment [5].

2.2. The multifunctional value of soil. Soil condition and soil quality

The physical, chemical and biological properties of soils result from the geological origin of the bedrock, environmental factors (climate, topography, etc.) and anthropogenic factors (agricultural practices, industrial pollutant emissions, geotechnical degradation, etc.). As soil performs a key role in many natural and anthropogenic systems, soil properties affect ecosystem services, environmental quality, agricultural sustainability, climate change, and human health.

The main soil functions are [2, 6]:

1. Environmental – participation of the soil cover in the shaping of the environment: local climate, water conditions, vegetation, and relief;
2. Ecological (living space and genetic resources) – an important element of energy flow as well as the circulation and retention of matter in the ecosystems;
3. Edaphic (natural resource) – soil creates conditions for the life of plants and animals;
4. Sociological (regulatory) – counteracting changes in the environment, climate change, neutralising the impact of human activity;
5. Economic (usable) – soil as a workshop, a farmer's place of work, people's place of life.

Soil health and soil quality are defined as the soil's ability to sustain biological productivity that contributes to maintaining the quality of the surrounding environment and human health [7]. These two terms are often used synonymously. It is important to distinguish that "*soil quality*" is related to soil function, while "*soil health*" determines soil as a finite, non-renewable, and dynamic living resource. Soil health involves the interactions between vegetation and soil to create a healthy environment [8]. In March 2021, the UN Agency's Intergovernmental Technical Group on Soils (ITPS) has defined soil health as "the ability to sustain productivity, diversity, and environmental services of terrestrial ecosystems". This is a starting point for setting comparable indicators on sustainable land management [9].

A healthy soil performs specific functions dependent on biological processes occurring in this system, e.g. carbon and nutrient cycling, structural preservation (mechanical properties of soils), and maintenance of homeostasis. A number of indicators are used to assess the soil condition in addition to physical and chemical properties, i.e. the composition of soil microbial communities [10, 11], enzyme activities [12, 13], and the presence of earthworms and nematodes [14, 15].

Soil, like air and water, is a fundamental natural resource supporting a variety of ecosystem goods and services for the benefit of humanity.

Soil functions in ecosystems are mainly:

- carbon sequestration,
- water treatment,
- groundwater recharge,
- pathogen population control,
- biological nitrogen fixation
- protection of biodiversity.

2.3. Soil quality indicators

The soil quality index SQI is a tool for monitoring soil health and assessing area management practices. In a recent study, Lenka et al. [16] identified a new approach to data transformation when the SQI is used on a regional scale. For routine soil quality monitoring, a data set from a depth of 0-15 cm is sufficient. The superiority of the soil function (SF) expressed in values of the SQI approach over the Principal Component Analysis Method (PCA) indicates that a minimal agro-ecological region-specific dataset can be created for long-term monitoring of soil health on a regional or national scale to maintain optimal soil productivity. The superiority of the soil function approach over principal component analysis method (PCA) means that a minimum data set specific to an agro-ecological region can be created for long-term monitoring of soil health on a regional or national scale to maintain optimal soil productivity. In general, it is recommended to use of linear scoring with a single value of maximum or minimum to assess soil quality [17]. The “lower is better” function is used as the indicator [18].

The Soil Management Assessment Framework (SMAF) provides site-specific interpretations of soil quality indicators [19]. As soil quality at a site depends on management objectives, climate, crops, and soil type, a framework approach is used to index soil quality. This allows for differentiation in the interpretation of the indicator results depending on the place and the purpose.

The structure of the index includes three main steps including [20]:

1. Selection of indicators for efficient and effective monitoring of critical soil functions;
2. Interpretation of indicators in terms of soil function (using expected ranges determined by the inherent capacity of soil);
3. Combining indicator results into an integrated soil quality indicator (optional). The result is a relative measure of the soil’s ability to perform the functions necessary for its intended use.

An example of SMAF, i.e. the transformation of selected indicators within the four soil functions into dimensionless values from 0 to 1 using the linear scoring method, is presented in Table 2.1.

Table 2.1

Exemplary soil functions, their indicators, and assigned weights [22]

Soil Function	Weight	Function Indicators	Weight	Scoring Function
Maintaining soil structure and water storage	0.35	Soil organic carbon	0.20	More is better
		Available water capacity	0.10	More is better
		Bulk density	0.05	Less is better
Nutrient supply function	0.25	$KMnO_4$ oxidizable C	0.05	More is better
		Available N	0.05	More is better
		Available P	0.05	More is better
		Available K	0.05	More is better
		Available S	0.05	More is better
Soil biological activity	0.20	Soil respiration	0.01	More is better
		Dehydrogenase	0.05	More is better
		Fluorescein diacetate	0.05	More is better
Soil basic properties, potential to limit production	0.20	pH	0.10	Optimum is better
		Exchange capacity (EC)	0.10	Less is better

In Poland, in the 1970s, an indicator for the valorisation of agricultural production space (VAPS) was developed at IUNG-PIB. The VAPS index reflects the potential of agricultural production space resulting from natural conditions. It is an integrated indicator based on the assessment of indicators of individual habitat elements, such as soil quality and suitability, soil water conditions, relief, and agroclimate. It was created to quantitatively and spatially assess the natural factors determining the potential crop yields on the local level (Tab. 2.2).

As a supplement to the VAPS indicator, the indicator of natural and tourism value (NTV) was developed. The selection of the indicators included in the NTV assumes that they should simply describe the relationship between agricultural activity and the natural-tourist values of rural areas. While determining the NTV, the share of stagnant waters, forests, and areas not subjected to anthropopressure in the total area as well as the share of permanent grasslands in the agricultural area should be taken into account. Research conducted in Poland by IUNG-PIB shows that VAPS is a good tool for designating areas characterised by special constraints. It makes it possible to identify areas where, due to low crop yields, the continuation of agricultural production is endangered, which consequently contributes to landscape degradation. According to IUNG-PIB, when the valorization is lower than the average, plant production becomes uncompetitive. Even though farmers change the direction of production from crops to livestock , irreversible changes in the landscape and environment may occur [21, 22].

Table 2.2

Index of agricultural production space valorization (VAPS) source IUNG [9]

Partial rate	Point range
Quality and usefulness of agricultural soils	18–95
Agroclimate	1–15
Terrain	0–5
Soil water relations	0.5–5
Total VAPS	**19.5–120**

Works related to the delimitation of areas with natural limitations (ANL) carried out in Poland since 2009 (art. 32 of Regulation No 1305/2013) have proved that not all areas with unfavourable conditions for agricultural production (especially those below 52 VAPS points) can be classified as areas with natural constraints based on biophysical criteria. To maintain the method consistent with the provisions of Regulation 1305/2013, a combination of NTV and VAPS was proposed (Tab. 2.3).

Table 2.3

Classification of areas with natural limitations

Nature and tourism value index NTV [points]*	Index of valorisation of agricultural production space VAPS**			
	≤52	52.1–66	66.1–72.5	>72.5
≤35.6	ANL qualification specific type	No ANL specific type		
35.7–53.4	ANL qualification specific type		No ANL specific type	
>53.4	ANL qualification specific type			No ANL specific type

*average for Poland – 35.6; ** average for Poland – 66.6

The monitoring of the quality of soils and land has been carried out in Poland since 1995. For this purpose, a national network consisting of 216 measurement and control points located on agricultural soils throughout the country was established. Changes in various characteristics of agriculturally used soils, especially chemical properties, occurring at specific time intervals under the influence of agricultural and non-agricultural human activity (anthropopressure) are monitored. The latest report covers the years 2020–2022 and is available on thehttps://www.gios.gov.pl website [23].

2.4. Trends in modern agriculture – optimal use of soil resources

The current Common Agricultural Policy emphasises the promotion of sustainable farming, which involves producing healthy and safe food in a way that improves the natural environment. In doing so, it points out that sustainable agriculture is made possible to a large extent by innovation, which consists of the creation and practical application of new production technologies, new services and products as well as new ways of organising work.

2.4.1. Conservation agriculture

Conservation Agriculture (CA) is a cultivation that leaves at least 30% of plant residues on the soil surface compared to conventional (plough) tillage. It involves reducing the intensity of treatments to the necessary minimum, i.e. as much as necessary and at the same time as little as possible. Loosening is carried out at a depth of 5 cm (shallow) to 30 cm (deep). The soil surface is covered all over the year with crop residues, mulch, or protective plants, which are on the surface or partially mixed with the soil. Considerable attention is also paid to a wide variety of rotations including intercropping and strip-till. The dependence of ecosystem properties on the type of crop is shown in Table 2.4 [24, 25].

According to Eurostat (2010), CA was practiced on 22.7 M ha, which was 25.8% of arable land in Europe. During the period from 1999 to 2013, the CA cropland area expanded at an average rate of about 8.3 M ha per year, from 72 to 157 M ha [26]. ECAF reports that in 2018 the adoption of CA in Europe increased from 1,500 thousand ha to about 2,900 thousand ha in 2018. Therefore, CA is considered to be the future of sustainable agriculture.

Table 2.4

Ecosystem properties in different cultivation technologies [24]

Properties	Traditional cultivation	Conservation agriculture	Grassland
Ecosystem	open	half-open	closed
Ecological balance	unbalanced	almost balanced	in balance
Availability of nutrients	short	mean	high
Maintaining organic matter	getting lower	it persists	it persists
Biomass content	getting lower	it increases	stabilised
Water retention	little	big	very big
Erosion	big	little	lack
Impact on soil quality	possibility of degradation	big	big

2.4.2. Precision agriculture

Precision farming is a comprehensive management system based on the adaptation of individual agrotechnical elements to varying conditions in specific parts of the field, depending on the current state of plant development and soil properties. Compute-assisted soil management contributes to the efficient management of production processes. Soil analyses are used to prepare abundance maps. Highly developed navigation and information technologies are used for data acquisition and processing (research drones, photodetection). During fertilisation, the doses of fertilisers are varied depending on the soil's richness, which allows for avoiding over-fertilisation in fields with variable abundance. The measurable effect becomes higher yields with better quality, while decreasing costs and labour inputs, and, importantly, reducing the environmental contamination. Precision farming is consistent with the assumption of the European Green Deal and is a tool for sustainable agricultural production aiming to reduce the use of fertilisers and plant protection products.

Proposals for cultivation technologies:

1. ***seed fertilisation*** is carried out at seed sowing. Fertilisers (usually ammonium phosphate) are placed slightly below the sown seed. This stimulates the root system for deeper rooting and ensures a good start for the plants. The expanded and deep root system retains fertiliser nutrients that are leaching out of the soil;
2. ***strip tillage*** involves cultivating narrow strips of soil where seeds and fertilisers are sown. The rest of the field remains un-tilled. Self-sowing of crops, e.g. cereals, prevents erosion and leaching of nutrients from the soil and reduces weed growth.

3. ***cultivation of plants for mutual benefit* –** plants that like to grow side by side, support each other, and prevent weeds from growing. In addition, they are selected so that they take up nutrients from different levels and have similar soil requirements. For example, “Three Sisters” (guild) are corn, beans, and pumpkin. The corn provides scaffolding for the beans. Beans provide corn and pumpkin with nitrogen. The pumpkin grows to shade the soil and inhibit the growth of weeds.

2.4.3. Organic farming

Organic production is an overall system of farm management and food production that combines environmentally preferable practices, a high degree of biodiversity, the conservation of natural resources, the application of high animal welfare standards, and a production method that meets the preference of some consumers for products made using natural substances and natural processes [27]. According to the EU’s “Farm to Fork” strategy, by 2030 the area of organic farming in the EU should account for at least 30% of the agricultural land. The Polish plan has a less ambitious target of only 7%. It seems achievable, since in 2021 the share of organic cultivation in Poland was 5%. This constitutes a considerable progress compared to 3.5% in 2020. The number of organic farms has also increased significantly in Poland (by almost 8%). According to the data of the Central Statistical Office (GUS in Poland), the area occupied by organic farming in Poland increased to about 550 000 ha.

2.4.4. Good agricultural practice

Good agricultural practice (GAP) – a set of practices allowing the production of safe food using all available methods and means. Pursuant to the EU recommendations, the “ordinary good agricultural practice” (OGAP) was introduced in Poland for farmers applying for financial support. The basic legal act regulating the principles of creating and implementing the agri-environmental program in the EU as well as in the candidate countries is Council Regulation (EC) No. 1257/1999 on support for rural development by the European Agricultural Guidance and Guarantee Fund (EAGGF). Detailed rules for the implementation of these programs and financial instruments were also created in the form of Council Regulation (EC) No. 445/2007 (EUR-Lex). Poland has a “Code of Good Agricultural Practice” developed by IUNG in Puławy, published in 2004 by the Polish Ministry of Agriculture and Rural Development and Ministry of the

Environment. It is mainly based on the UNECE Framework Code (2001) [30] and contains:

1. Law protecting the environment in the field of agriculture;
2. Arrangement and management of a farm in sustainable agriculture;
3. Water protection;
4. Agricultural land protection;
5. Air protection;
6. Protecting the landscape and preserving biodiversity;
7. Rural infrastructure;
8. A set of principles of good agricultural practice for the implementation of the Directive on the reduction of ammonia emissions.

Polish Code for Good Agriculture Practice (PCGAP) is systematically updated depending on European and global trends in soil management. In Poland, for example, the regulation on the so-called “nitrogen program” was announced in the Journal of Laws on 7 February 2023. The changes include, among others, flexible dates of spring fertilisation or the method of calculating doses of nitrogen fertilizers. This information can be found on popular messengers such as Twitter, Facebook, etc. The Polish Institute of Meteorology and Water Management (IMWM) has prepared new functionalities on the “agrometeo.imgw.pl” website, thanks to which the farmer can make decisions on the fertilisation. On the IMWM website, a list of districts where it will be possible to apply fertilizers earlier (in spring) will be published daily, taking into account the average daily air temperature and rainfall intensity.

2.4.5. Agroforestry (agroforestry system)

Agroforestry (AF) is a land-use method that involves the simultaneous cultivation of trees and field/green crops in the same area. Trees and shrubs are intentionally integrated with plant and animal production for environmental and economic benefits. AF combines the goals of agriculture (crop production) and forestry (management, care and use of forests). This system is an alternative to land deforestation for agricultural production. Trees have a protective function for soils (anti-erosion, improvement of water balance, reduction of the risk of frost, etc.), thereby contributing to an increase in crop yields in the long term. The main purpose of tree cultivation in combination with traditional plant production or animal grazing is the production of biomass for energy purposes or high-quality wood [28].

2.5. Sustainable soil fertilisation

Assessing soil fertility enables the determination of a long-term nutrient management strategy. The nutrient balance is a method of optimising fertilisation. In the balanced fertilisation system, it is assumed that the input of nutrients in fertilisers should be equal to their uptake with crop yields. This is a certain simplification because the uptake of nutrients from fertilisers is not 100% and certain surplus of fertilisers is inevitable. Sustainable fertilisation is about managing nutrients and adequately supplementing deficiencies.

An essential tool for the proper management of nutrients in plant production, and thus limiting losses of nutrients from agriculture, is the fertilisation plan (nitrogen, phosphorus, etc.). Excessive fertilisation leads to economic losses, resulting from higher costs incurred for the purchase of industrial inputs of production as well as lower crop yields, both in terms of their weight and quality. The result of overfertilization is also polluting the environment. Excess of unused nutrients enter the ground, surface water (lakes, rivers), and the atmosphere. Too little fertilisation also has a negative impact on the environment. A deficit of even one nutrient (nitrogen, phosphorus, or potassium) contributes to the underutilisation of soil productivity, plant production potential, and lower yields. Nutrient deficiency also leads to a reduction in soil fertility and, over time, even to soil degradation. It is, therefore, important to adjust fertilisation to the nutritional needs of plants and soil conditions. For economic reasons, there is a need to conduct production in a way that ensures effective management of all nutrients.

2.5.1. Sustainable nitrogen fertilisation. The cost of reducing ammonia emissions

Balanced nitrogen management is a set of all nitrogen application practices on a farm used to achieve agronomic and environmental goals. Agronomic objectives refer to achieving good yields and crop quality as well as optimal productivity and animal welfare. The environmental objectives relate to minimising nitrogen losses from agriculture in a gaseous form (nitrous oxide, ammonia) and nitrogen leaching, thus reducing climate change [29, 30].

Nitrogen management on the farm involves taking steps each year to analyse the nitrogen needs of plants and animals, determine the availability of different nitrogen sources and the conditions under which nitrogen is stored, and consider the possibility of nitrogen losses and an appropriate efficient nitrogen practice. Restrictions on the agricultural use of nitrogen fertilisers result from the principles of sustainable management of the soil environment.

The Polish Code of Good Agricultural Practice PCGAP [31] informs about the need to analyse the content of nutrients content regionally and specifically for farm types. Their improvement or dosing should be evaluated every five years. The dose of the nitrogen input to agricultural land in fertilizers may not exceed 170 kg N in the pure component per hectare of agricultural land annually [31, 32]. A positive gross nitrogen balance in the range of 30–70 kg N per 1 hectare of agricultural land is considered environmentally safe. A nitrogen fertilisation plan is an essential tool for proper nutrient management in crop production and one of the most important practices to reduce nitrogen losses from agriculture. The obligation to draw up a nitrogen fertilisation plan was included in the nitrate program, which defines the entities obliged to draw it up and its scope. It is recommended to analyse the mineral nitrogen (N_{min}) content in the soil at least once every 4 years.

Experts from institutes supervised by the Minister of Agriculture and Rural Development have elaborated a series of practices that can be applied in Polish agriculture to reduce ammonia emissions into the atmosphere. PCGAP recommends the use of low-emission fertiliser distribution and storage techniques and the rationalization of nitrogen fertilisation (Tab. 2.5). In addition, it discusses practices of housing and feeding of animals.

Table 2.5

Reduction of ammonia emissions with the use of natural fertilisers [30]

Type of fertiliser	Land use	Reduction of ammonia emissions in %	Limitation of applicability
Liquid natural fertilizer	Cultivated fields, including new crops, grasses, crops	90% – instant ploughing 70% – immediate cultivation (no soil inversion) 45–65% – introduction into the soil within 4 h 24–30% – introduction into the soil within 24 h	Fields under cultivation
Manure	Cultivated fields, including new crops, grasses	90% – instant ploughing 60% – immediate cultivation (no soil inversion) 45–65% – introduction into the soil within 4 h 50% – introduction into the soil within 12 h 30% – introduction into the soil within 24 h	Fields under cultivation

The overriding aim in the selection of practices is to reduce ammonia emissions, taking into account the costs of the application and the scale of implementation difficulties. An approximate calculation of ammonia reduction costs depending on the type of fertiliser and the method of its application is presented in Tables 2.6 and 2.7.

Table 2.6

Cost calculation of ammonia emission reduction using urea inhibitors and fertiliser in a polymer coating for different types of crops [24, 31]

Crop type	Urea inhibitors		Fertiliser granules in a polymer coating	
	Euro cost/Ha	Euro cost/kg saved - NH_3	Euro cost/Ha	Euro cost/kg N-NH_3 saved
Field crops	4.22	0.49	15.50	1.8
Horticultural crops	6.50		23.87	
Permanent crops	2.74		10.04	
Mean	4.48		16.47	

Table 2.7

Cost calculation of ammonia emission reduction using soil application into the crack and through cultivation for different types of crops [24, 31]

Crop type	Soil application into the crack		Soil application through cultivation	
	Cost Euro/Ha	Euro cost/kg saved - NH_3	Cost Euro/Ha	Euro cost/kg N-NH_3 saved
Field crops	22.01	0.96	6.42	0.45
Horticultural crops	12.73	0.36	20.33	0.92
Permanent crops	no date	no date	29.76	3.20
Mean	17.37	0.66	18.83	1.52

Krysztoforski [24] calculated the costs of nutrient losses (Tab. 2.8) assuming:

1 kg N = 17 kg of grain or eutrophication of 454 m^3 of water

1 kg of P_2O_5 = 6 kg of grain or eutrophication of 1905 m^3 of water

Table 2.8

Approximate cost of nutrient loss due to unsustainable fertilisation [24]

	Nitrogen cost* per kg N	Phosphorus cost* per kg P_2O_5
Component cost	1 kg x PLN 2.91/kg = 2.91 PLN (≈ 0.66 EUR)	1 kg x PLN 3.67/kg = 3.67 PLN (≈ 0.83 EUR)
Lost grain growth	17 kg x PLN 0.65/kg = 11.05 PLN (≈ 0.66 EUR)	6 kg x PLN 0.65/kg = 3.9 PLN (≈ 0.88 EUR)
Social cost / Water treatment	454 m^3 of water = a lot	1.905 m^3 of water = a lot

* assuming that eutrophication occurs at a concentration of 0.7 mg PO_4/dm^3 or 0.525 mg P_2O_5 and 2.2 mg N-NO_3/dm^3

In addition to the calculable losses of fertiliser components (fertiliser prices and yield loss), there are hidden costs of contamination of flowing waters (rivers, lakes) and the Baltic Sea. The social costs, which are difficult to estimate, include the consequences of water pollution, which are paid for by the whole society in the form of water purification costs, health care, impoverishment of the natural environment, loss of biodiversity, etc.

The EU pursues a long-term policy of improving air quality to a level that does not cause negative effects or risks to human health and the environment. Directive (EU) 2016/2284 of the European Parliament and of the Council of 14 December 2016 was announced on the reduction of national emissions of certain atmospheric pollutants, known as the NEC Directive, was promulgated. The individual methods of reducing ammonia emissions are consistent with the recommendations contained in the 2014 United Nations Economic Commission for Europe (UNECE) Code of Good Agriculture Practice (CGAP) for reducing ammonia emissions and at the same time constitute their development. In Poland, an appendix to the CGAP regarding the reduction of ammonia emissions was announced in 2019 (www_6). A consistent approach in this respect is justified by the fact that both the Nitrates Directive and the NEC Directive are crucial from the point of view of adapting the agricultural sector to activities related to the implementation of the EU's requirements in the field of broadly understood environmental and climate protection policy. These EU legal regulations are implemented due to various objectives (water and air protection, respectively) and concern various polluting substances, and the implementation of the requirements resulting from them in agricultural practice is currently at different stages in each country.

2.5.2. Shaping soil organic carbon levels (sequestration) and climate change

At the beginning of this century, it was estimated that carbon contained in soils accounts for 75% of the total organic carbon (C_{org}) storage [33]. The most important link in the Earth's carbon cycle is the soil. It is possible to reduce CO_2 emissions into the atmosphere and prevent climate warming by increasing the content of C bound in terrestrial ecosystems through a process known as sequestration [34, 35]. The greatest accumulation of organic carbon occurs in two ecosystems: agricultural and forestry. However, the abundance of C in the agricultural ecosystem is characterised by greater controllability [36].

The surface horizons of soils are characterised by the highest C content, which is related to the supply of organic remains from above-ground parts of plants and animals as well as from root systems and organisms living directly in the soil. Only part of the organic matter (OM) reaching the soil with the remains of organisms is converted into specific humus compounds that are quite permanently bound in the soil. A large part of OM is used as a source of energy for soil organisms, and a certain part (despite the occurrence of humification processes) is leached into deep soil horizons and groundwater beyond the reach of root systems. The amount of C_{org} accumulation in the soil depends on the type of vegetation cover and the type of soil humus. Activities that encourage carbon sequestration will not prevent the effects of climate change by themselves, but they are one of the methods of reducing them [37, 38]. To be truly effective, they must be used on a large scale. There are many initiatives that encourage farmers to change the farming system and facilitate those activities. Some of these incentives involve rewarding farmers who cultivate the land to retain as much carbon as possible. In Poland, direct payments have been implemented since 2023, the so-called "carbon farming" for implementing practices beneficial to the environment, climate and animal welfare that go beyond basic requirements. One of the initiatives supporting carbon sequestration is also the Bayer's programme, through which activities that encourage C storage in the soil are supported and rewarded in 14 countries. Recent scientific developments recommend changing farming practices (conversion of arable land to grassland, conservation tillage, i.e. mixing crop residues into the soil, reduced tillage, and cover crops) to increase carbon sequestration in agricultural soils [39]. Recent studies have shown that combining a diverse organic crop rotation (e.g. three-year clover crop) with compost may be one way for agricultural systems to provide stable soil C sequestration [40].

The presence of soil organic matter (SOM) results in the retention and enhancement of carbon stocks. This contributes to climate change mitigation, while generating benefits for agriculture, food security and nutrition, ecosystem service provision, and climate change adaptation in support of many SDGs. Investing in SOM is a cost-effective and feasible climate change mitigation option that simultaneously improves soil health and quality [41].

Increasing the soil organic carbon pool in agricultural soils through the implementation of sustainable soil management practices can contribute not only to the reduction of greenhouse gas emissions [42]. It supports the achievement of land degradation neutrality by 2030 (SDG 15.3) and is a prerequisite for the subsequent achievement of climate neutrality on the continent in 2050 [43].

2.5.3. Soil pH regulation

An important issue that determines the uptake of nutrients is the correct soil pH, adapted to the requirements of the plant or land use. Forested land, for example, is acidic and this is not the result of degradation but the nature of OM. Decaying needles cause the forming humus to have a low pH. Therefore, unsuitable habitat conditions make plants develop worse, and this is of particular importance in orchards. Inadequate pH is one of the causes of poor yields. For example, it is a mistake to grow blueberries on soils that have a pH of 6, because the site requirements indicate that it should be 4.5.

Liming is a process of neutralising the acid reaction of the soil, although this treatment is most often associated with reducing the negative impact of aluminium and heavy metals. The most important thing about this treatment is that it contributes to maintaining (creating) an appropriate soil structure. Humus and calcium ions, in addition to clay minerals and bacterial slimes, form the binder of soil aggregates. By regulating the soil pH, the calcium-saturated mineral-organic colloids cement the lumps, which formaggregated structures [44]. Acidic soils have an unfavourable structure, which means poor water retention capacity. Low pH also limits the development of the root system, thereby affecting how plants cope with periods of drought. Plants with a well-developed root system can absorb water from deeper layers of the soil. In contrast, plants with a weaker root system dry out quicker.

Lime treatment significantly reduces the effects of drought. However, in order to have a positive effect on the soil structure, it is important that the amount and type of the applied calcium fertilizer is based on a soil analysis as well as the soil and crop type. Treatments that increase the humus content of the soil and improve soil pH also counteract the effects of drought and restore the soil’s yield potential.

Research conducted by IUNG shows that soils in Poland are acidic. In the last decade, the share of soils with an optimum pH range (5.6–7.2) has decreased, the share of acidic soils has slightly decreased, and what is very worrying, the share of very acidic soils with a pH < 4.5 has increased significantly. In 2020, a soil liming program was introduced in Poland to counteract the progressive degradation of soils. It is mainly based on financial support for the individual activities of farmers.

2.5.4. Soil water storage

Agro-technology includes all procedures of soil treatments, i.e. tillage, fertilisation, sowing or planting, irrigation as well as plant care and protection. It is important to reduce or actually stop the water soaking and evaporation by developing wastelands, and in agriculture by post-harvest tillage (soil management methods). For example, in order to store as much water as possible in the soil, it is necessary to avoid leaving a ploughed field for the winter. Soil covered with vegetation or crop residues stores water better and is not eroded. Weed infestation of crops must also be prevented. Weeds are better adapted to drought than crops. To counteract the weed growth, care should be taken to improve the fertility of the soil by increasing the OM content. Most soils in Poland are poor in humus, with an average humus content of 1.9 percent. Humus retains five times more water than it weighs, so it is an irreplaceable store of water in periods of drought. Raising the level of humus content of the soil is a long-term process. The results of the research carried out by IUNG in Puławy as part of the Monitoring of Arable Soils Chemistry in Poland show that the percentage of soils with a low humus content has recently increased, while the percentage with a very high humus content has decreased.

Soil structure affects the retention of water in the soil. Particularly important is the ability of humic acids (HAs) to create a lumpy soil structure. HAs regulate the soil structure on both sandy (increasing compactness) and heavy soils (loosening and aeration). The electrodynamic properties of fulvic acids (FAs), also perform an important role in breaking up excessively compacted soil colloids. In the presence of FAs, even very moist soil retains a lumpy structure. In contrast, in waterlogged or flooded soils, FAs improve aeration.

Plants are provided with even amounts of water and nutrients through the growing season if they grow on soils with the right structure. In soils with a stable structure, plants are guaranteed 85% water use. In contrast, on soils where this structure is disturbed, water use is usually below 15%. Soils that have lost or are losing structure are unable to store the volume of water required by plants. Crops grown on unstructured soils perform worse in periods of drought compared to those grown on structured soils. Structured soils also tolerate excess rainfall better. The use of preparations containing HAs supports structure-forming processes. This type of solution is recommended for “tired” and less fertile soils that have lost their natural structure or those frequently flooded by heavy rainfall. The application of humic products stimulates the biological activity of the soil, ameliorates its buffering properties, and improves the availability and use of nutrients in the soil system. Favourably, preparations containing HAs influence the sorption properties of the soil and enhance the development of the root system as well as its uptake of nutrients and water.

2.6. Soil as an environment

Soil is considered a non-renewable resource, meaning that its loss cannot be recovered during a human lifetime, as topsoil can take more than 500 years to form [45]. It can take up to 1000 years to form one centimetre of soil. As the human population grows, comprehensive soil management practices become increasingly important [46]. The development of research on the soil cover reflects the rapid changes in the environment influenced by both civilisational and natural factors. Interdisciplinary experimental teams that study not only the spatial structure of intact natural soil, but also cultural, industrial, and urban soils, are becoming a strength in the sustainable management of the soil environment. In the ongoing research, it becomes important to clarify the impact of natural and anthropogenic factors on the formation of soil diversity in time and space.

Spreading awareness of sustainable soil management practices is one of the key factors for climate change adaptation, not only in agriculture. The development of systemic, optimised and locally adapted solutions should involve all soil users. This means going beyond the traditional agronomic and economic knowledge schemes. It points to the need to analyse the interactions between soil, water, atmosphere, biodiversity and landscape.

2.6.1. Interdisciplinary perspective of soil research

Soil condition is a very important element of the biological environment that affects all ecosystems. In the context of sustainable development and soil management, it becomes necessary to move away from the traditional approach towards a more general and multi-directional one. In the traditional approach, “soil science” treats soils as research objects that are natural systems with clearly vertical differentiation of soil properties. Degórski [6] indicates greater possibilities for soil inference based on the use of, for example, soil geography (Fig. 2.2).

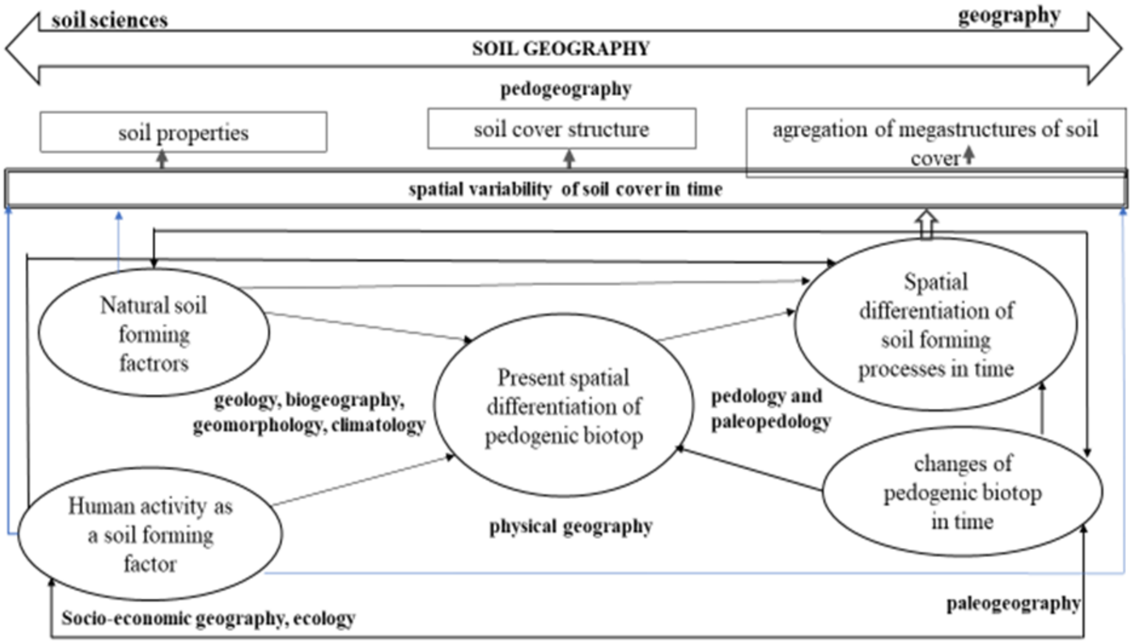

Fig. 2.2. Relationships between soil science and geography [6]
Rys. 2.2. Związki między gleboznawstwem a geografią [6]

"Soil geography" is subjected to scientific inference procedures aimed at explaining the reasons for heterogeneity and geographic variability on micro to mega scales. In the face of such conditions, "soil geography" can be defined as a scientific discipline, both within geography and soil science, dealing with the distribution of soils on the Earth's surface (or part of it) and the causes underlying their spatial variability. This variability is determined by the chronological (changes over time) and chorological (variation due to fauna and flora activity) influence of both natural and anthropogenic soil-forming factors. Soil geography has the potential to become a progressive sub-discipline of geography oriented towards nomological research aimed at discovering regularities, relations, and relationships occurring in the environment [6].

Nomological disciplines build cause-and-effect interpretations based on empirical models, allowing the formulation of generalisations and construction of functional-structural models (Fig. 2.3). Understanding the connections is the key to making specific assumptions to achieve the goals of the SDS without losing soil functionality.

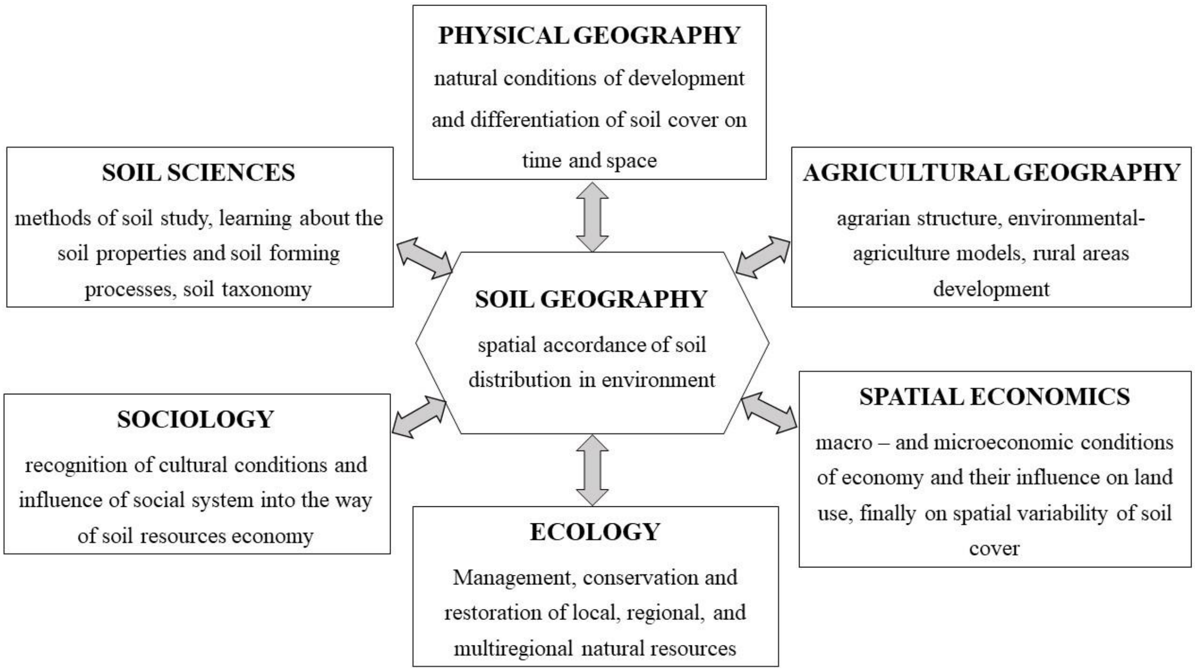

Fig. 2.3. Connections of soil geography with other fields of science [6]
Rys. 2.3. Powiązania geografii gleb z innymi dziedzinami nauki [6]

2.6.2. Soil degradation

Soil degradation is the deterioration of soil due to misuse or mismanagement, usually for agricultural, industrial, or urban purposes. The main causes of degradation are pollution, salinisation, erosion (leaching), and compaction (sealing).

A pollution ranking, calculated based on the frequency of occurrence of a specific pollutant and the source of pollution, prepared by the European Environmental Agency EEA signalled in 2012 a strong pollution (71%) of land in Europe mainly with heavy metals and mineral oils (Fig. 2.4a). The main source of pollution was announced as industrial production and commercial services (Fig 2.4b). Since then, trends in the management of contaminated sites have been positive; however, the levels of national action vary considerably across the EU. There are currently estimated 2.8 million potentially contaminated sites in the EU. Most of them are post-industrial areas. These estimates are considered conservative and the number of potentially contaminated sites across the EU is likely to be underestimated depending on which polluting activities are considered [47]. A large number of undetected or suspected contaminated sites poses a serious threat to human health and the environment.

Even though many regulations have been established for agricultural activities obliging farms to comply with cross-compliance requirements, there is still a risk of soil contamination (Tab. 2.9). Sources of pollution can be reduced through rational fertilisation management and sustainable use of soils, applying the principle of "as little as possible and as much as necessary".

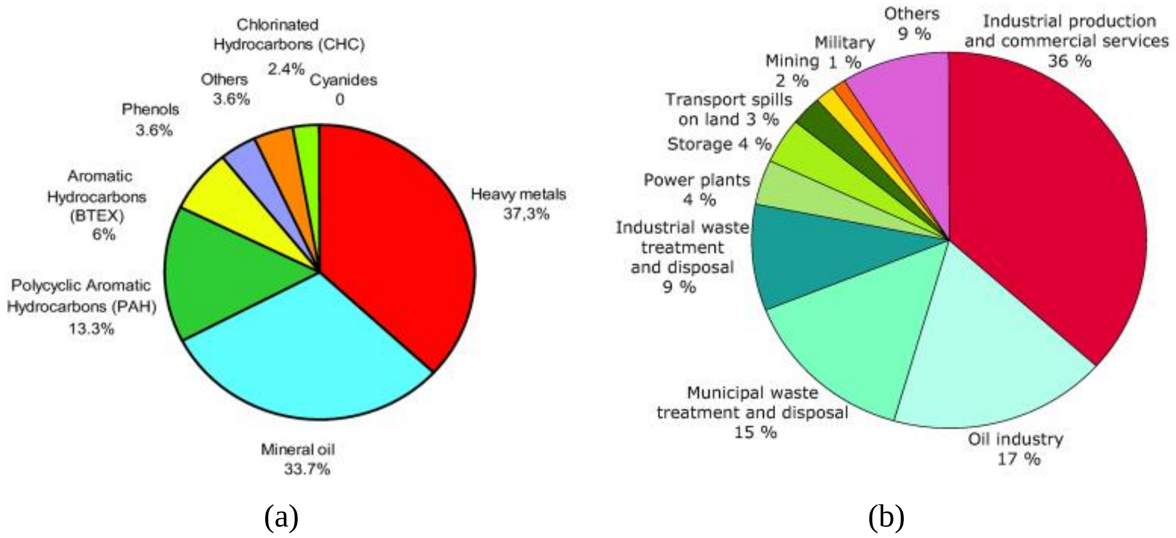

Fig. 2.4. Contamination in Europe: a) contaminants affecting soil and groundwater [48] b) sources of contamination [49]
Rys. 2.4. Zanieczyszczenie w Europie: a) zanieczyszczenia wpływające na glebę i wody gruntowe [48], b) źródła zanieczyszczeń [49]

Table 2.9

Types of contamination in agriculture [50]

Type of pollution	Environmental effects	Sources of contamination
plant nutrients, mainly nitrates and phosphates	worsening of drinking water quality, excessive development of plankton in surface waters, water blooms	mineral and natural fertilisers applied in excessive doses or in the wrong way
toxic substances – plant protection products, heavy metals	water contamination, threat to biological life in water, exclusion of water from recreation	chemical plant protection, use of sewage sludge and industrial compost
fine inorganic and organic suspended soil particles	threat to biological life, exclusion from recreation, difficult water transfer	water and wind erosion, improper use of natural and organic fertilisers

Soil water erosion is about 1.6 times higher than the rate of soil formation on all land and two times higher in an EU agricultural land [51]. Soil sealing is an intensive form of land degradation and 2.43% of EU land is sealed [47]. Soil organic carbon stocks in European peatlands could decline by 13–36% by the end of this century [52]. Biodiversity has declined in all regions of Europe. For example, earthworm species richness has been negatively affected by increased land use intensity [53].

2.6.3. Reducing the negative impact of industry on the soil environment

Industrial pollution in Europe is declining due to a combination of regulation, production development and environmentally friendly initiatives. However, the industry continues to pollute the environment, and the pursuit of eliminating pollutant emissions in this sector is an ambitious challenge.

The intensive industrial development, currently referred to as the “fourth industrial revolution”, will lead to an increase in greenhouse gas emissions, resulting in climate change. Starting from 2010, the upward trend in GGE continues and the “carbon footprint” increases. Actions are being taken to adapt selected methods and implement technologies that, as innovations in a company, will contribute to increasing its eco-efficiency. Eco-efficiency is linked to the “carbon footprint”. It can be defined as maintaining existing growth by offering the customer products and services at a competitive price, meeting their expectations, while minimising the environmental impact and resources consumption of resources throughout the product life cycle. To increase eco-efficiency, the company can (i) reduce the consumption of materials and excess inventory, (ii) reduce energy consumption, (iii) reduce toxic substances, (iv) increase the share of recycling in waste recovery, (v) increase the share of renewable substances and renewable energy sources, (vi) increase product durability, etc.

Solutions to minimise the effects of industry activities should meet the assumptions regarding stocks, waste, and emissions of harmful compounds. Such solutions also include clean logistics processes as well as eco-driving and eco-friendly solutions during the construction and operation phases of the facility. When imposing the goal of reducing the carbon footprint, a company should combine methods with technologies.

2.7. Ecological soil biodiversity

Soil ecological biodiversity is essential and indispensable for environmental sustainability. Biodiversity influences the fertility and health of soils and the provision of ecosystem services.

The ecosystem services provided by soil are [54]:

- stimulating the circulation of nutrients,
- regulation of water flow and storage;
- biological regulation of pests and diseases;
- maintaining the structure of the soil;

- decomposition of xenobiotics;
- regulation of the composition of the atmosphere (greenhouse gases).

Highly biodiverse soils require less fertilisers and various types of agrochemicals. Healthy soil is inhabited by various groups of organisms. Each group performs a specific function in the cycles of matter and energy, but they are dependent on each other. Disrupting the activity of one group has consequences for the next [55]. The effects of measures aiming to conserve biodiversity are usually visible in the long term.

Nature has its own regulatory and protective mechanisms against too many undesirable organisms, so the diversity and balance of many species prevent pathogens from multiplying too much. In a soil populated by beneficial microorganisms, pathogens are less likely to develop a large population, but it is not worth eliminating any species altogether. Losses caused by a small population of pathogens will not exceed the economic damage threshold. However, their population may be associated with another group of organisms. The extinction of one group implies the extinction of others, and this is a simple way to upsetting the biological balance.

Dead microorganisms are a source of nutrients for plants. They are also a carbon reservoir. In acidic soils and those with a reduced humus content, biological activity is impaired, which also affects the mineralisation of residues, and the availability of components and the soil structure-forming process.

Introducing innovative agricultural practices together with new technologies can be a step forward, as envisaged by the soil and food health mission under the research framework program “Horizon” with started in 2021. Horizon is a tool to raise awareness about the importance of soils, engage citizens, create knowledge and develop solutions to restore soil health and function. New tools and methodologies (e.g., genomics, DNA and RNA sequencing) are further expanding scientific knowledge on soil health [56].

In order to support the conservation of biodiversity in the EU, the European Biodiversity Strategy 2030 has been formulated [57]. Within the scope of the strategy, it is planned to establish a coherent network of protected areas, provide legal protection to at least 30% of the EU’s land areas and 30% of the EU’s marine areas and to establish ecological corridors. Within the scope of the strategy, a mission called “soil action plan for Europe” has been formulated. Within this mission, it is planned to establish research units in which various entities: scientists, farmers, foresters, and specialists in spatial planning will carry out research and implement their results [58]. The aim of the cooperation is to preserve and restore resilient soils to prevent desertification, protect soil organic carbon stocks, stop soil sealing and increase the use of urban soils, reduce soil pollution as well as prevent erosion, improve soil structure to increase soil biodiversity and educational activities to improve public awareness of the issue.

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3. SUSTAINABLE APPROACH TO WATER CONSUMPTION

Water, as the basis of life on Earth, is also a crucial element in almost all branches of the industry. Water constitutes an inseparable element of every field of anthropogenic activities, therefore, also for sustainable production [1]. Tahir et al. [2] pointed out that in 2030 the global freshwater demand could exceed the viable resources by about 40% if noting changes in the current business-as-usual approach to freshwater consumption. In addition, the available water resources are under increasing pressure caused by the industrialisation of almost every inhabited region of the world [3]. Therefore, there is a strong need to search for methods and strategies which allow for water reuse and the recovery of valuable products which can act as pollutants in water streams, to achieve sustainable water management in all branches of the industry.

3.1. Water scarcity in Europe

Water scarcity and even drought are becoming a visible problem in an increasing number of areas around the world. The issue of water scarcity is often associated with countries located in the desert zone. However, water scarcity also affects countries in Europe, leading to environmental and economic consequences that become worse due to irreversible climate change [4]. Bressers et al. [5] noted that the south of the continent is more prone to drought than the northern part of Europe, where the drought phenomenon is generally not recognised as a significant issue. Generally, the water engineering sector is more focused on water surplus occurring periodically during flooding than on water shortage during drought. This could be related to the fact that flooding is more visible to a bigger range of the population than drought. However, even if there is no public awareness of water scarcity, that does not mean it does not exist in a given region. According to data presented by EDO-European Drought Observatory [6] using the Combined Drought Indicator (CDI) v3.0, almost all European countries in the last decade were affected by the phenomenon of drought, which has a significant impact on agriculture. For example, in February 2023, warning conditions for drought were noted in France, Ireland, the United Kingdom, southern Spain, Switzerland and northern Italy, the regions of Romania and Bulgaria close to the Black Sea, Greece and the Mediterranean Islands [7]. Those conditions were similar to the ones in 2022. The drought situation for April 2023 was presented in Figure 3.1. Monitoring the water scarcity situation caused by drought allowed for future forecasting of the occurrence of crisis situations and the development of possibilities to minimise them [8], which is particularly important for the agricultural industry. Water scarcity in Europe has an impact not only on agriculture but also on nature and freshwater reservoirs. Therefore, it strongly impacts the whole economy and human health.

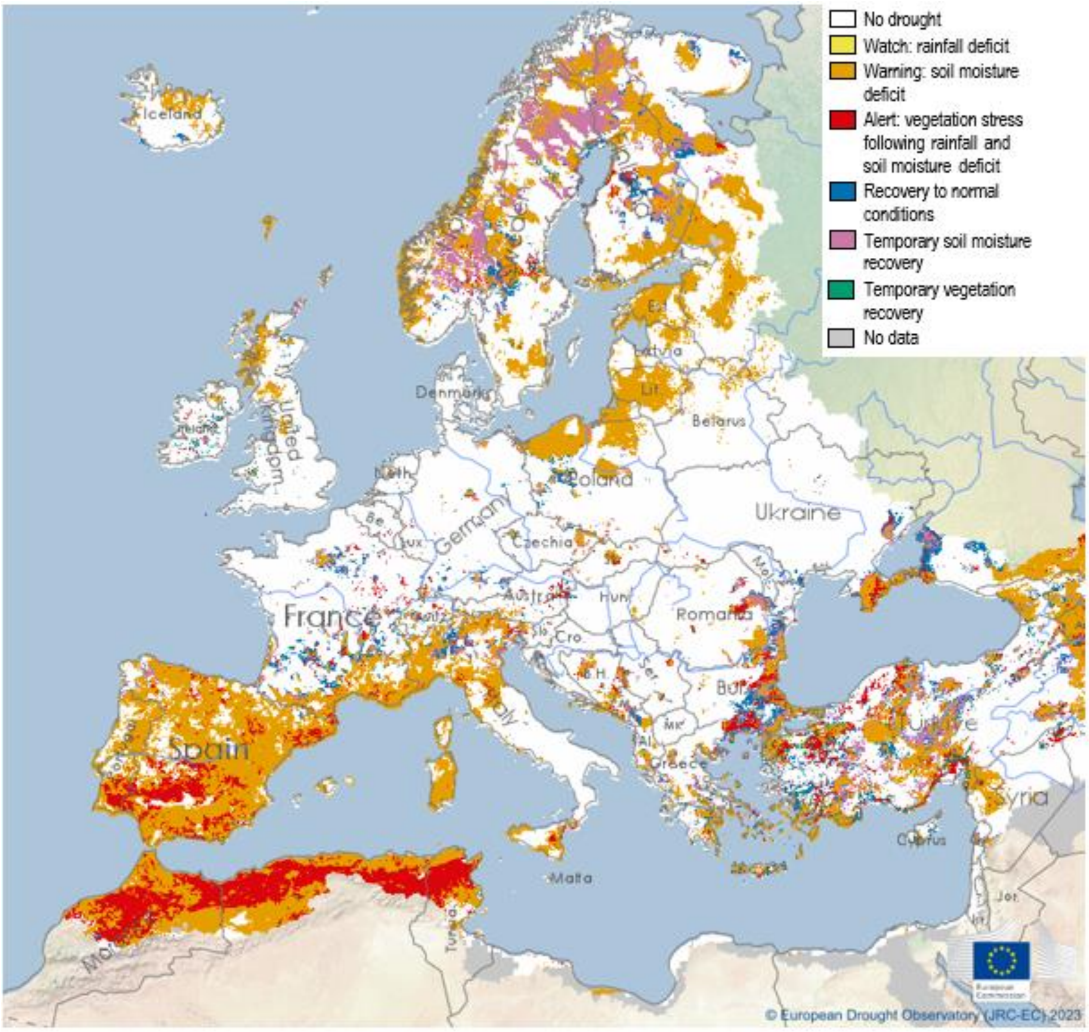

Fig. 3.1. European drought situation in April 2023 according to the CDI-v3 [9]
Rys. 3.1. Sytuacja suszy w Europie w kwietniu 2023 r. wg CDI-v3 [9]

Water scarcity is becoming an emerging concern due to population growth which increases the water demand. The European Commission predicts the intensification of agricultural water use to satisfy the increased food demand [10].

The problem of water scarcity is related not only to the lack of access to any kind of water or drying up of areas but, in global terms, also concerns the lack of access to water of appropriate quality. The continuously growing freshwater scarcity threatened the sustainable development of the human society for a few decades [11, 12]. During the World Economic Forum in 2015, the water supply crisis was pointed as the top 1 high-impact risk for the human population and the whole planet [13]. Greve et al. [14] pointed out that global water consumption has increased nearly eight times in the past century and is now about 4600 km^3 per year and is expected to increase by 20–30% by 2050. He et al. [15] indicated that by 2050 nearly half the number of the world's large cities would be located in regions with high-water scarcity, affecting up to 2.373 billion people.

The understanding of the water sacristy as a complex problem depending on different factors is important for governments to formulate policies on global, regional and local scales. However, water management is considered a local question and water-related issues are becoming global problems [16]. To facilitate the assessment of the status of water scarcity in different parts of the world, many indicators have been developed, which are based on measurements of water availability, access, capacity, use and environment [12]. These Water Scarcity Indicators include:

- Falkenmark indicator – defined as the per-capita water availability [17, 18];
- Criticality ratio – shows the ratio of water use to availability [19];
- International Water Management Institute IWMI indicator – indicates the proportion of water supply as water availability by accounting for the water infrastructure [20];
- Water Poverty Index WPI – given as an average of water availability, access, capacity, use and environment [21];
- Water footprint-based assessment – defined as the ratio of water footprint to water availability [22];
- Life cycle assessment-based water stress indicator – shows the ratio of water use of water footprint to availability [23];
- Cumulative abstraction to demand ratio [24];
- Green-blue water scarcity – given as the requirement versus availability of green-blue water resources [25];
- Quantity–quality-environmental flow requirement (QQE) indicator – Incorporating water quality, quantity and environmental flow requirements [26].

For sustainable production and consumption, it seems most reasonable to use the water footprint. This indicator measures the amount of water that is necessary to produce goods and services for human use [22]. The water footprint-based assessment is based on three alternatives for the estimation of water use and availability:

- The water use was described by the consumptive use of surface- and groundwater flows – blue water footprint.
- The necessary flows to sustain critical ecological functions of water bodies were subtracted from water availability.
- The use and availability of water resources were measured on a monthly basis rather to consider the seasonal water scarcity in a giver region.

Several studies [27, 28] have found an influence of commercial trade chains on water scarcity in distant economies. The virtual water trade can alleviate water scarcity in some areas but, at the same time, it exacerbates water scarcity in other regions [29, 30]. Therefore, an in-depth analysis of the virtual water trade in different sectors and regions is also crucial in understanding the changing global water scarcity [31]. Liu et al. [12] pointed out five future research challenges and directions, which include the validation of water scarcity indicators, the incorporation of water quality as well as environmental flow requirements in water scarcity assessments, the temporal and spatial scales of water scarcity with green and virtual water, and strong cooperation between hydrological, water quality, water ecosystem science and social science communities.

3.2. Anthropogenic pollution of water resources

The problem of water scarcity is compounded by the presence of an increasing number of pollutants in the water. The acceleration of the industry, on the one hand, guarantees constant civilisation development by improving the quality of life and increasing urbanisation and, on the other hand, it is a source of environmental pollution with substances toxic to humans [32]. The development of analytical techniques has revealed the scale of the problem and has proven the ever-increasing concentration of individual contaminants. In recent decades, the world economy has focused on activities mitigating the deepening water crisis and preventing its spread to regions of the world previously considered not threatened by a lack of access to water. These activities consist, among others, in limiting the pollution of the aquatic environment by monitoring and implementing rational strategies for managing raw materials in all industries, especially those that significantly contribute to the spread of various types of pollution. Among the industries that significantly affect the deterioration of water quality, the following should be mentioned: pharmaceutical, refinery, textile, chemical, tanning and mining. However, almost every human activity is associated with introducing pollutants into the environment. These substances, together with natural generated pollutants, that may potentially adversely affect the natural environment, are referred in the literature as contaminants of emerging concern, CECs. Devi et al. [33] list emerging water contaminants with their effects and major sources (Tab. 3.1). These groups of compounds, unlike CECs, have been extensively analysed for their origin and health impacts. Compounds belonging to these groups can cause changes in animal and human behaviour and landscape, strongly affect aquatic ecosystems, and therefore lead to a decrease in water resources for private and industrial uses.

Table 3.1

Emerging water contaminants, their effects and major sources according to Devi et al. [33]

Type of contaminant	Proven adverse effects	Major source
Pharmaceuticals	Unknown	Wastewater
Antibiotic resistance genes	Pathogen resistance to antibiotics	Human and animal antibiotics
Endocrine-disrupting compounds and personal care products	Endocrine system disruption	Wastewater
Alkylphenolpolyethoxylates	Toxicity	Degradation of surfactants
Methyltertbutylether	Toxicity	Fuel oxygenate
Perchlorate	Uncertain	Rocket and missile propellant
1,4-Dioxane	Carcinogenesis	Stabiliser of solvents
N-nitrosodimethylamine	Carcinogenesis	By-product of wastewater chlorination
Fluorinated alkyl surfactants	Toxicity	Industrial processes
Polybrominated diphenyl ethers	Toxicity	Flame retardants
Benzotriazoles	Toxicity	Anticorrosive agents, wastewater
Naphthenic acids	Toxicity	Crude oil, wastewater
New, chiral, and transformed pesticides	Toxicity, carcinogenesis	Wastewater
Disinfection by-products	Toxicity	Chlorination by-products of emerging contaminants
Cyanotoxins	Liver and nervous system damage	Blue-green algae
Human parasites, bacteria, viruses	Infections	Wastewater
Zoonotic parasites, bacteria, viruses pathogenic to humans	Infections	Animal waste

The most simplified classification of pollutants divides them into natural and anthropogenic pollutants, which in turn are divided by their nature into organic and inorganic. Water pollutants can also be categorised considering their environment entering way as a point source, nonpoint source, or transboundary source. They can be ordered as biodegradable or nonbiodegradable and hazardous or non-hazardous compounds [34]. Dudziak [35] proposed an addition calcification that divided compounds into ones subjected and non-subjected to legal regulations.

Ghangrekar and Chatterjee [36] proposed a classification of water pollutants that divided them into eight categories:

- Organic pollutants,
- Pathogens,
- Nutrients and agriculture runoff,
- Suspended solids and sediments,
- Inorganic pollutants (salts and metals),
- Thermal pollution,
- Radioactive pollutants,
- Nanopollutants.

However, all listed compounds can be classified as inorganic or organic compounds with special attention to microplastic.

3.2.1. Inorganic compounds

Inorganic pollutants are considered nonbiodegradable compounds with a toxic nature, which, even at a trace concentration, can lead to adverse negative effects on water ecosystems and human health [37]. These pollutants came into water resources mainly from naturally occurring activities (released from the earth's crust) and anthropogenic contributions such as urbanisation, industrialisation, uncontrolled discharge of sewerage, discharge of not properly treated wastewater, etc. The increasing consumption of inorganic compounds occurring in the Earth's crust leads to harmful changes in the ecological system and can potentially damage large parts of the environment. Therefore, it is crucial to regulate activities causing their release and elevated level in water sources. Sauve and Desrosiers [38] pointed out that technological interventions are required for their reliable monitoring as well as effective remediation of water bodies polluted by inorganic contaminants. The U.S. Environment Protection Agency [33] listed the following inorganic materials as water quality parameters:

arsenic, antimony, boron, beryllium, barium, chloride, calcium, copper, cadmium, chromium, cobalt, lead, iron, fluoride, manganese, molybdenum, magnesium, mercury, nitrate, nickel, nitrite, phosphates, potassium, phosphorus, salmonella, selenium, silica, sodium, silver, sulfate, sulfide, tin, tellurium, thallium, titanium, uranium, tritium, vanadium, zinc. However, it should be noted that these materials may be considered inorganic pollutants only when their limit exceeds permissible values [33]. The term inorganic impurities does not only refer to heavy metals but also to trace elements, mineral acids, sulfates, inorganic salts, metals, complexes of metals with compounds and cyanides.

Examples of inorganic pollutants which can have a negative impact on water quality and, therefore, make the water unsuitable as a source of portable or industrial water, among others, are:

- Ammonia – is released in water from food processing industries, agricultural waste, manufacture of plastics, fibres, paper, explosives, and rubber [39]. The concentration of ammonia in water changes during the season and depends on the surrounding land use, temperature and pH [40]. Ammonia is not only harmful to living organisms, but it can also become a serious problem when occurring in technical water by causing corrosion [41];
- Arsenic – is widely used in various branches of industry, such as electronics, metallurgy, agriculture, wood preservation and medicine [42]. Arsenic can exist in four forms, which are arsine, arsenic, arsenate and arsenite. However, the most prevalent forms detected in water are arsenite and arsenate [43]. This inorganic pollutant is highly toxic to all life forms [44] and is classified as a carcinogenic substance [45]. The highest arsenic water pollution in European countries was noted in Hungary, Serbia and Romania [46].
- Barium – originates from the wastes of metal, oil and gas industries and the erosion of the Earth's crust. The maximum concentration limit of barium in drinking water of 2 mg/dm^3 given by the U.S. Environmental Protection Agency. It was reduced by World Health Organization to less than 0.7 mg/dm^3 [47]. The occurrence of barium in water, which comes into contact with saltwater containing SO_4^{2-} and CO_3^{2-} anions, leads to the formation of large crystals such as $CaSO_4$, $BaSO_4$ and $SrSO_4$ [48]. These compounds can cause the blockage of pipelines, pumps, heaters and chillers, which lead to high economic and operational costs.
- Chloride – comes to the water from both natural and anthropogenic sources with the surface runoff from salt storage, salt used for road de-icing, industrial effluent, landfill leachates, gas drilling, septic tank effluents, animal feeds, irrigation drainage

and seawater intrusion in the coastal areas [49]. High chloride concentration can cause salinisation, which is near water scarcity, a widespread environmental and economic problem [50].

- Chromium – is discharged into water bodies from dyes, paints and leather tanning industries [51]. Chromium can exist in the environment as trivalent Cr(III) and hexavalent Cr(VI) [52], while the hexavalent form is five hundred times more toxic than the trivalent form [53]. The tolerable limit of dissolved chromium in drinking water was set at 0.05 mg/dm^3, and for total chromium at 2 mg/dm^3 [54].
- Copper – is released in water mainly from corrosion of water plumbing units and agricultural application. Vargas et al. [55] pointed out that the consumption of 0.3 mg/dm^3 can cause stomach cramps and intestinal diseases.
- Mercury – is a very harmful and toxic inorganic contaminant with global public health concerns [56]. Witkowska et al. [57] pointed out that mercury is responsible for reproductive disorders, genotoxicity, carcinogenicity, endocrine disruption and immunosuppression. It is released in water from scale gold mining, fossil fuel burning, production of nonferrous metals, cement production, chloro-alkali industry [58]. Moreover, mercury tends to settle in sediment and accumulate in biological tissues [59].
- Uranium – is a rare element, and it can be found in water due to mining or refining of nuclear fuels or radioactive waste.
- Zinc – a metal used in corrosion-resistant coatings, alloys, dry-cell batteries, plastics, wood preservatives, rubber, dyes, paints and cosmetics. Therefore, zinc comes into the water from the related industries' waste streams as well as from the metal production processes, waste incineration, industrial combustion of coal and the degradation of zinc-containing products. According to Geiger and Cooper [60], the overconsumption of zinc can cause various health problems: nausea and stomach cramps, lungs disease and disorders of the body temperature control system.

3.2.2. Organic micropollutants – contaminants of emerging concern

The United States Environmental Protection Agency USEPA [61], together with the United States Geological Survey USGS [62], describe the CECs as any chemical that is detected in the water environment but was not previously naturally present in it and may affect the aquatic organisms. CSCs are ubiquitous in various elements of the environment and were considered persistent or hardly biodegradable and, therefore, pose or potentially pose a threat to human health and the natural environment [63]. The CECs group includes a wide range of micropollutants belonging to pharmaceutical compounds and personal care products PPCPs, estrogenic micropollutants EDCs, flame retardants, pesticides and food additives [64–66]. In addition, this group can include any substance present in the environment that may have a negative impact on any of the elements of the ecosystem. Due to such a broad framework of CECs classification, it seems to be impossible to clearly specify the current number of chemical compounds described by this term. Meijer et al. [67] developed a software – CECscreen, that counts the number of known CECs mentioned in various sources while excluding duplications and inorganic compounds. The openly accessible CECscreen software determined the presence of 69,526 compounds with CAS No. and 306,279 intermediates of these compounds, which were found and described in the environment. Salimi et al. [68] proposed a classification of selected CECs most often described in the literature, considering their application (Tab. 3.2).

Table 3.2

Salimi et al. classification of selected CECs

Compound group	Application
Pharmaceutical compounds and personal care products:	
painkillers	analgesic effect
antiepileptic drugs	anticonvulsant effect
antihyperlipidemic drugs	lipid regulators
non-steroidal analgesics and anti-inflammatory drugs	analgesic, anti-inflammatory effect
antimicrobial agents	antibiotics antiseptics
polycyclic musks	fragrances
other	insect repellers, fragrances, stimulators
Estrogenic Compounds:	
hormones	hormones
alkylphenols	production of household goods and industrial products
polyaromatic compounds	
organic oxygen compounds	plasticizers, industrial production of polycarbonates and epoxy resins
other	by-products of various combustion and industrial processes
Flame retardants	reduce the flammability of substances
Pesticides:	
carbamates	herbicides, insecticides, fungicides
chloroacetanilides	pre-emergence herbicides
chlorophenoxic acids	herbicides

Table 3.2 cont.

organochlorine pesticides	insecticides
organic phosphates	insecticides
pyrethroids	insecticides
triazines	herbicides
other	
Food additives:	
artificial sweeteners	sweeteners
antioxidants	food preservation
Dyes	colouring substances

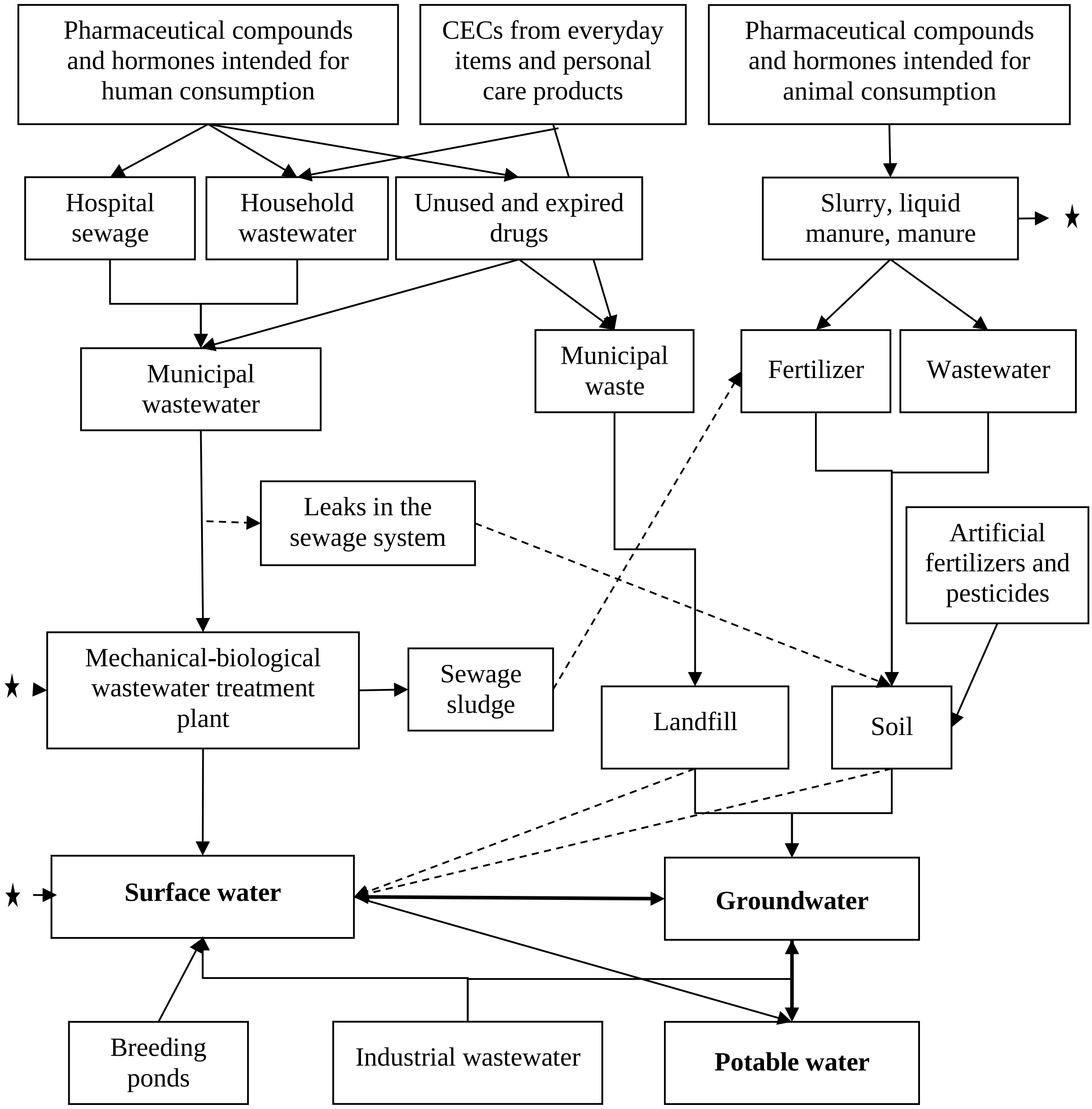

Fig. 3.2. Sources and routes of CECs entering the aquatic environment
Rys. 3.2. Źródła oraz drogi przedostawania się CECs do środowiska wodnego

Migration paths of CECs as well as emerging water contaminants and inorganic contaminants to the environment, can be broadly divided into a point and non-point ones [69]. While the pathways of their transformation cover all elements of the ecosystem [35]. Figure 3.2 shows the routes of CECs getting into both surface and ground waters.

It should be noted that, as in the case of all anthropogenic micropollutants, the primary source of CECs in the environment is municipal, industrial and agricultural sewage, as well as leachate from landfills [70]. This is related to the level of persistence of individual CECs, which may not be decomposed in conventional wastewater treatment systems and may enter the aquatic environment unchanged [71] or transform into other newly formed pollutants. The persistence of CECs was proven in several studies. For example, Loos et al. [72], during the analysis of wastewater in 90 wastewater treatment plants located in Europe, showed the presence of 159 different CECs in the raw sewage, of which 125 were also present in treated wastewater leaving these facilities. Tijani et al. [73] and Luo et al. [74] prove that the number and concentration of CECs in treated wastewater discharged to water receivers strictly depend on the capacity and efficiency of the treatment plant and the speed of pollutant decomposition processes taking place in the technological line. Yan et al. [75] indicate that concentrations of pharmaceutical compounds in wastewater may be present in several ng/dm^3, and similar concentrations occur in treated wastewater discharged to surface receivers. Therefore, CECs are identified not only in wastewater but also in surface and groundwater, which is the source of tap and technical water in many industry branches. Erickson et al. [76], after the analysis of 118 water samples taken from wells located in urban areas of Minnesota, USA, proved the presence of 35 different CECs. Moreover, the number of compounds detected in 35% of the tested samples ranged from one to ten different specifics, including, among others, such compounds as 4-tert-octylphenol, caffeine, triclosan and 17α-ethinylestradiol. Sousa et al. [77], in their review, compiled the frequency of occurrence in the aquatic environment of 66 CECs listed in Directive 2013/39/EU of the European Parliament and of the Council of 12 August 2013 [78] as priority substances and in the Commission Implementing Decision (EU) 2015/495 of 20 March 2015 as CECs [79]. The study showed that pharmaceutical CECs were most often identified in the water environment, while natural and synthetic hormones were monitored on five continents [80–84] and pesticides on four [85–88]. The most frequently identified compound among those monitored was imidacloprid, with a concentration in surface waters in Spain reaching even 656 ng/dm^3 [89]. Also, the environmental concentration of the 17α-ethinylestradiol, which is a synthetic oestrogen, and is used in contraceptive pills [90], was as high as 1822 ng/dm^3

[91], while the nonsteroidal anti-inflammatory drug diclofenac concentration in Antarctic surface waters was 7761 ng/dm^3 [92]. Research by Bendz et al. [23] in waters taken from rivers in Sweden indicated the presence of butylhydroxytoluene – an antioxidative food additive – at a concentration of 620 ng/dm^3. Whereas Esteban et al. [93], in their research on the occurrence of CECs in the surface waters of Spain, observed that 19 out of 30 compounds tested by them had concentrations ranging from 2.2 ng/dm^3 to 5.9 μg/dm^3.

Landrigan et al. [94] pointed out that exposure to various environmental factors, including micropollutants, is the main factor in the occurrence of numerous dysfunctions, diseases and premature death, not only in the broadly understood world of fauna and flora but also in the human population. Only a small number of anthropogenic substances that are used daily and released into the environment have been tested for their impact on organisms and have safe levels for plants, animals and humans. However, Vermeulen et al. [95] indicated that there is no information on the impact of CECs decomposition by-products and their biotic and abiotic transformation products. Santos et al. [96] report that acute toxicity has only been determined in the case of 150 specifics classified as pharmaceutical compounds. In the case of pesticides, the Aquatic Life Benchmark (ALB) database, prepared by the US Environmental Protection Agency USEPA, can be used for the indication of potentially toxic concentrations of pesticides [97]. However, there is still the need to investigate the impact of micropollutants belonging to other sub-groups of CECs and their intermediates. The presence of CECs in water is not only a health issue but also makes the water unsuitable for industry uses.

3.2.3. Microplastics

Another harmful pollutant group are microplastics. The U.S. National Oceanic and Atmospheric Administration [98] and the European Chemicals Agency [99] define microplastics as microscopic fragments of any type of plastic that are less than 5 mm in length. A more detailed description of microplastic was given by The International Organization for Standardization. In the ISO/TR 21960:2020 standard terms and definitions, microplastics are described as any solid plastic particle insoluble in water with dimensions between 1 μm and 1000 μm [100].

Microplastic can enter the water environment directly or be generated from a secondary source, that is, to be formed as a result of large plastic debris destruction by weathering owing to physical and chemical processes occurring in the water environment. The primary microplastics include microbeads added to cosmetic products or cleaning agents [101]. The literature [102] indicated that microbeads do not undergo natural degradation caused by biological or photochemical processes and are also resistant to thermal degradation. Therefore, the legislation in various countries decided to prohibit the addition of these types of microplastic to related products and, at the same time, prohibit the sales, import and export of any type of microbeads. For example, the United States, by the introduction of the Microbead-Free Waters Act of 2015, reduced the use of microbeads [103]. On 1 January 2018, Decree No. 2017-291 of 6 March 2017 on the conditions for implementing the prohibition on the placing on the market of cosmetic products rinsed for exfoliation or cleaning with solid plastic particles and cotton swabs for domestic use came into force in France [104]. The Swedish Chemicals Agency has already expressed a positive opinion for the introduction of a national ban on the use of microbeads in Sweden [105]. The United Kingdom banned the use of microbeads by the Environmental Protection (Microbeads) (England) Regulations 2017 No. 1312 [106], and in 2020 Ireland banned the use of microbeads in household and industrial cleaners [107]. Duis and Coors [108] pointed out that the majority of microplastics identified in the environment are of secondary origin. There is, therefore, no simple way to limit the amount of their release to water. Mitrano and Wohlleben [109] suggested that only the closing of all plastic life cycles by the circular economy, recycling, and chemcycling can be an effective way to limit the negative environmental impact of these pollutants.

The major source of microplastics in water are different types of plastic elements that come into contact with water. Microplastic particles can be released into the water even in drinking water treatment plants and tap water distribution systems. Wang et al. [110], as well as Pivokonsky et al. [111], indicated that polyacrylamide coagulants used in the coagulation/sedimentation processes remain in the treated water. Even polymer membrane separation processes, which should separate microcontaminants from water, can be a source of microplastic [112]. The polymer membranes may break down during the main filtration process, the cleaning procedure or due the aging process and release microplastic [113]. Zhang et al. [114] pointed out that the number of microplastic particles ingested from tap water could reach 4700 items/year. The legislation systems do not specify related standards or policies regarding the permissible concentration of microplastics and do not even specify processes for directly removing these types of contaminants [115].

3.3. Proper water management

Water resources should be treated as the most valuable good, and efforts to ensure their proper quality and adequate consumption should become the fundamental priority of every human being. Such actions will provide not only financial savings in the management of water resources in given industries but also ensure constant access to water, guaranteeing the development of any company in the coming decades. Proper water management should correspond to the guidelines provided by the circular economy of water, which is strongly connected with new alternative technologies and practices that allow for water recovery from wastewater streams [116]. This approach allows for the cessation of exploitation of new non-renewable water resources and, therefore, of destabilisation of the ecosystem. The use of rainwater, greywater, and nutrient recovery from wastewater should also be considered.

Qtaishat et al. [117], after an analysis of the circular water economy in the European Union, proposes the following five directions for the improvement of policies and regulations connected to circular water technologies:

- Implementation of the fit-for-purpose water principle. This approach will result in the reduction of losses of water resources related to unnecessary water abstraction of portable water quality, cost savings by the treatment processes and the availability of water for different uses. The fit-for-purpose water principle also forces new and innovative wastewater service innovation models which promote the circular lifecycle of water.
- The policy, guidelines, protocols and processes addressed to circular water reuse should reflect the context, required water quality and scale of the system. These should lead to an easier permission process for small-scale solutions.
- Implementation of cost and financial risk mitigation strategies. This can be achieved by allocating investments and incentives at separate deployment scales: water capture, treatment, distribution and use. Such an approach forces the assessment of the lifecycle’s costs, benefits and risks. It should be noted that the incentives should be targeted at these entities which were capable of providing the necessary infrastructure and upscaling possibilities.
- Identification of the process, performance and route-to-market gaps. Different types and numbers of permissions issued by regulatory bodies or authorities are required in different European countries. The duration for obtaining permits and the complexity of bureaucracy also differ between the countries. This is not beneficial

for small-scale systems providers, who may lack administrative expertise to navigate the various requirements. This makes the system less profitable. Also, reporting and monitoring processes of the already existing solutions require several corrections.

- The improvement of knowledge and awareness across all sectors and user groups.

Among all industry branches, agriculture exerts the most significant pressure on the available freshwater resources. According to the information provided by the United Nations World Water Development Report [118], agricultural activities consume 90% of water resources in some developing countries. For this industry, it is difficult to push through solutions based on the assumptions of a closed water cycle. However, the use of solutions allowing for the collection and storage of rainwater, which could be an alternative source of water for surface and underground waters, should be considered.

For many industry branches, variated desalination processes are the most favorable solutions to fill the water availability and demand gap. Nevertheless, this technology is quite expensive, in some cases harmful to the environment [119] and does not solve the issue of proper wastewater management [120]. Several studies [121–127] indicate the possibility of effective treatment of water streams from different types of impurities in advanced oxidation processes, which can be carried out as single processes or combined with other treatment processes such as activated sludge, sorption or filtration. The main challenge in choosing and performing any kind of water treatment procedure is properly selecting reaction factors and operating parameters of individual processes to ensure complete retention or removal of pollutants without creating the possibility of the decomposition by-product generation. The decomposition intermediates are often more toxic than the parent compounds [128]. Some intermediates can also be dangerous to the water supply system and cause damage to some of the components of these systems critical for the society and the industry.

3.4. Water supply systems

The infrastructure used for the water supply and treatment can be centralised or decentralised in a given region. For European countries, the centralised model of those systems is predominant [129]. The centralised water systems consist of extensive treatment facilities and distribution networks for the connection of distant water sources and recipients (households and the industry) and a top-down governance model [130]. This system requires from 1% to 6% of the country’s annual GDP [131]. Customers can use only one type of water service with impeded alternatives for transformative water management [129].

On the other hand, rigid centralised water is required to operate properly in a fast and ever-changing environment and to maintain its service delivery at an affordable cost, considering the increasing consumer standards [132]. The decentralised water system is based on integrated and multifunction water infrastructure characterised by small ecological footprints which use locally available water sources. This increases the resiliency and sustainability of urban water systems [133]. The decentralised system is a solution based on Sustainable Urban Water Management, which forces the integrated and adaptive management of the whole water cycle and the efficient use of water resources using flexible solutions at different scales [133]. Some examples of decentralised systems are greywater recycling, rainwater and stormwater harvesting, and water reclamation infrastructure. Schramm and Felmeden [134] showed that the implementation of decentralised infrastructure improved the system security, allowed for the adaptability of the system to changes in operation conditions and resulted in water resource conservation and energy and cost efficiency. The concept of sustainable water management based on guidelines povided by Marlow et al. [133] and Leigh et al. [135] is shown in Figure 3.3.

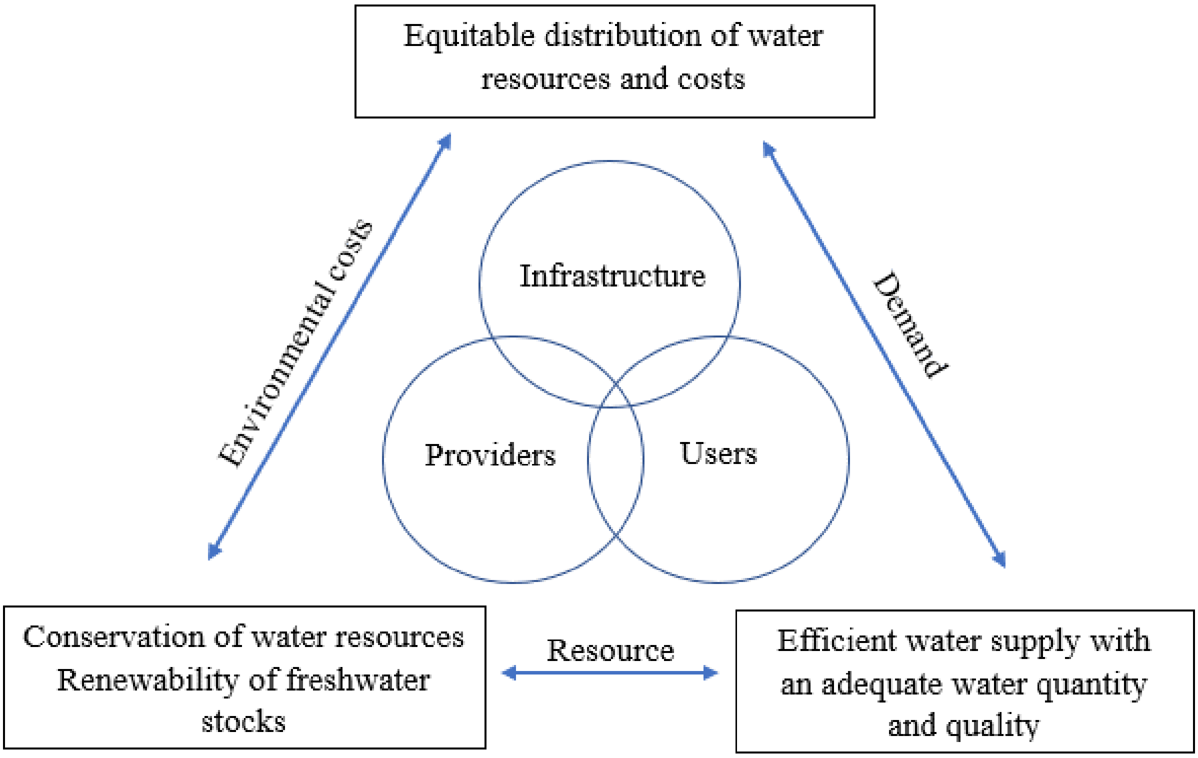

Fig. 3.3. Schematic concept of sustainable water management
Rys. 3.3. Schematyczna koncepcja zrównoważonej gospodarki wodnej

The water distribution systems are made of metal or plastic. The metals (cast iron, steel or copper) corrode due to their thermodynamic instability, thus affecting not only the life of the distribution network itself but also the quality of water. Also, biocorrosion, which is usually considered marginal, especially in factories supplied with tap water, could become an important issue, especially in new installations [136]. If the given industry branch requires steel water pipes, it is possible to protect them with a covering layer of zinc or zinc alloy. However, Delaunois et al. [137] pointed out that galvanized steel could also be corroded by the action of microorganisms.

The use of plastic pipes poses another problem – the release of microplastics, which is still not fully understood and is the subject of numerous recent studies. Tong et al. [138] pointed out that polyvinyl chloride (PVC), polyethylene (PE), polyamide (PA) and polypropylene (PP) pipes or fittings, which are the most commonly used plastic pipes [139,140], may be significant sources of microplastic in tap water. Epoxy resins, which were used to coat iron pipes, can also be the source of microplastics in tap water [141].

Not only the material of the pipes decides about the occurrence and the scale of the biocorrosion phenomenon. Pizarro and Vargas [142] showed that the water flow also impacted the microbially influenced corrosion. The occurrence of periodic increases in the flow might induce the growth of biofilm followed by the rise of the sum of bacteria in the water and, in the case of copper pipes, an increase in copper release. This is related to the detachment of corrosion intermediates and bacteria from the walls of the pipelines.

Particular attention should be paid to industrial cooling and heating systems in which water is the main medium. Those systems are extreme aqueous environments with high-temperature differences and high pH. Even the low nutrient availability does not protect the systems against microbially influenced corrosion caused mainly by alkalitolerant sulfate-reducing bacteria such as *Desulfonatronum*, *Desulfonatronovibrio*, and *Desulfotomaculum* [143]. Biocorrosion reduces the efficiency of industrial cooling circuits and can cause leakage, which leads to substantial financial losses.

3.5. Summary

Water, as one of the most crucial resources for every part of the industry and every human being, requires special care. Even the smallest actions to reduce water consumption, reuse or reduce water pollution can be crucial for the economy and the well-being of the society. Knowledge of the types of pollutants present in water and their ways of getting into the aquatic environment allowed for developing various strategies to counteract the progressing degradation of water. Issues related to water treatment using effective but, at the same time, energy-saving methods will be a challenge for environmental engineering in the coming decades. Proper water management based on the assumptions of the circular economy can not only be beneficial for the environment, but it can also bring profits to various industry branches allowing for savings related to fees for the discharge of sewage and the collection of water from central water networks. A comprehensive approach to water savings, and thus sustainable production and consumption, is also associated with monitoring the condition of the water distribution system and its adaptation to the requirements of a given industry. This allows extending the system's life and avoiding secondary water contamination by corrosive elements.

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4. SUSTAINABLE WASTEWATER TREATMENT AND MANAGEMENT

4.1. Introduction/history of the wastewater treatment

After the invention of agricultural practices and animal husbandry, believed to have originated in Mesopotamia, humans transitioned from a nomadic lifestyle to permanent settlements. This shift towards settled communities led to an increased reliance on water availability, as well as the emergence of the necessity to effectively handle the wastewater generated by these settlements [1, 2]

According to Lafrano and Brown [3], the evolution of sanitation systems can be divided into five main periods (Fig. 4.1):

- Early history;
- Roman period;
- Sanitary Dark Age;
- Age od Sanitary Enlightenment and the Industrial Age;
- Age of stringent environmental standards.

As early as 2500 BC, the world's first sanitation systems existed in Harappa and Mehenjo-Daro (India). Not only was there a direct connection from houses to the street sewer system, but the sewage had to undergo some pretreatment beforehand. Sewage was passed through tapered terra cotta pipes into a small sump. Solids settled and accumulated in the manhole, while liquids overflowed into the street drainage channels [3].

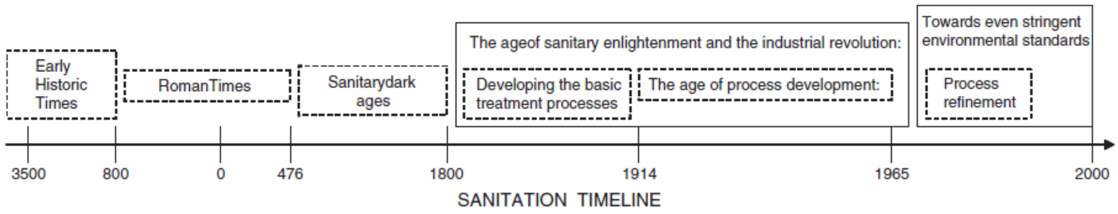

Fig. 4.1. Evolution of sanitation [3]
Rys. 4.1. Ewolucja systemów sanitarnych [3]

The development of civilisation allowed the development of advanced water supply as well as sewage disposal systems (dams, wells, aqueducts, sewage and drainage systems, toilets or recreational structures). This was driven by, among other things, the desire to raise the standard of living, and hence the Greek (including Minoan) and Roman civilisations developed advanced and comfortable lifestyles with public or private bathrooms and with flush toilets which can only be compared to modern systems of the early 20th century. The sophistication of these systems can be evidenced, among other things, by the cloaca maxima, which was a huge sewage disposal system capable of "servicing" a city with a population of one million. This system was expanded over the years, from simple open canals to closed giant canals in which one could even travel by boat, where the width of the canal reached up to 3.2 metres and its height up to 4.2 meters. However, these types of facilities only collected pollution and then discharged it into nearby lakes, rivers or the sea. This undoubtedly improved the quality of life in the cities; however, it only transferred pollution from one place to another [4, 5].

The collapse of the Roman empire also caused the collapse of the culture associated with water supply and sewage disposal. Water was taken directly from rivers and wells and then discharged without treatment, sometimes even directly into the street which was also one of the reasons for the spread of diseases and epidemics. At that time, the glorious exception were monasteries, which were equipped with systems for supplying water but also for discharging sewage. [3, 4]. It was not until the 19th century with the development of cities and water supply systems, that the situation improved with the construction of sewage systems. However, it was still a time when wastewater was discharged directly into the soil and water, and the way to treat it was believed to be dilution. This resulted in heavy pollution of the water environment and numerous cholera epidemics. It was not until the second half of the 19th century that it was understood that in order to ensure a supply of clean water, sewage must also be treated in some way [4]. Although the late 19th century brought the development of septic tanks invented in the 1860s by L.H. Mouras and the development of biological methods in the form of biological beds, it was not until the 20th century that a revolution in wastewater management and treatment took place. The undisputed breakthrough came in 1914 when Arden and Lockett invented activated sludge technology [6], which is the basis of biological wastewater treatment to this day. Most modern wastewater treatment plants have been designed to meet local requirements for treated wastewater quality. Undoubtedly, however, recent years have brought a number of challenges in terms of achieving energy neutrality, minimising sludge production, recovering nutrients, or removing micropollutants [7].

4.2. Municipal wastewater characteristics

In general, we can define wastewater as used water discharged after the use in households or generated in technological processes, including rainwater and infiltration water in sewers [8]. In the case of domestic wastewater, it is a mixture of human feaces, urine and grey water that mainly comes from washing, bathing and food preparation [5]. In general, the concentrations of pollutants and the amount of wastewater are variable during the hours of the day or seasonally. They depend on household water consumption, lifestyle and standard of living, the size of the locality or its characteristics. The main pollutants and their concentrations present in wastewater are shown in Table 4.1.

Table 4.1

Typical composition of untreated domestic wastewater [5]

Contaminants	Concentration [g/m^3]		
	Low	Moderate	High
Solids, total	350	720	1200
Dissolved solids	250	500	850
Suspended solids	100	220	350
Biochemical oxygen demand (BOD)	110	220	400
Total organic carbon (TOC)	80	160	290
Chemical oxygen demand (COD)	250	500	1000
Nitrogen (total as N)	20	40	85
Phosphorus (total as P)	4	8	15

Wastewater comprises a mixture of mineral and organic substances that pose challenges when attempting to identify them as individual organic compounds. To assess the overall organic compound content in wastewater, various indicators are used, including biochemical oxygen demand (BOD), chemical oxygen demand (COD) and total organic carbon (TOC). Among these indicators, the five-day biochemical oxygen demand (BOD_5) is widely employed due to the occurrence of biological oxidation processes over a span of five days, resulting in approximately 68% of organic matter oxidation. Conversely, the BOD_5 to COD ratio determines the degree to which wastewater is susceptible to biological decomposition. If the BOD_5/COD ratio ranges between 0.5 and 0.7, it indicates the presence of easily degradable substances in wastewater. On the other hand, a lower BOD_5/COD ratio implies a higher concentration of biologically undegradable substances in wastewater [9]. Due to the increased awareness of the environmental impact of wastewater and advancements in analytical techniques, advanced treatment methods are becoming increasingly prevalent in developed nations. While conventional wastewater treatment plants traditionally focused on secondary treatment and the reduction of carbon-based pollutants, the prevention of eutrophication has emerged as the subsequent objective in wastewater treatment. Depending on the characteristics of the receiving water bodies, numerous treatment plants are now mandated to remove nitrogen, phosphorus, or both, in order to mitigate eutrophication [3].

4.3. Nutrients – from removal to recovery

Freshwater pollution poses a significant challenge, particularly regarding the discharge of nutrients (nitrogen and phosphorus) into surface water, which accelerates the process of eutrophication. While natural eutrophication occurs over thousands of years, human activities have led to a rapid intensification of this process by increasing the input of aquatic plant nutrients into water bodies. As a result, the term “eutrophication” is now closely associated with “excessive fertilisation” referring to the input of abundant aquatic plant nutrients that trigger the overgrowth of algae and/or aquatic macrophytes in water bodies [10]. Over the past few decades, numerous water bodies worldwide have been impacted by eutrophication, including the Baltic Sea, which is particularly vulnerable to the environmental consequences of human activities due to its unique geographical and climatic characteristics. Consequently, it is essential to treat wastewater appropriately before discharging it into the environment, as untreated wastewater cannot be directly released [11].

4.3.1. Nitrogen removal

Nitrogen performs a crucial role in living organisms as a component of proteins. However, it is also considered one of the nutrients that contribute to eutrophication issues. Nowadays, biological methods have become widely employed for the treatment of municipal wastewater and certain industrial sewage. In most wastewater treatment plants (WWTPs), the removal of nitrogen is achieved through the process of biological nitrification/denitrification.

Nitrification/denitrification

Currently, the nitrogen removal process in conventional wastewater treatment plants relies primarily on two key processes: nitrification and denitrification. During nitrification, ammonium nitrogen undergoes oxidation in two stages, resulting in the formation of nitrate. In the subsequent denitrification process, the nitrate is further reduced to gaseous nitrogen. Figure 4.2 provides a visual representation outlining the nitrification and denitrification processes.

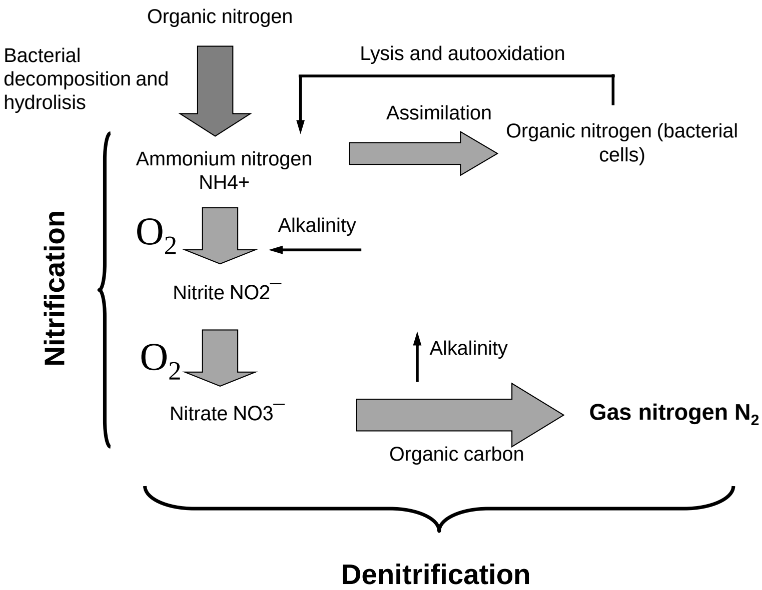

Fig. 4.2. Transformations of nitrogen compounds in classical wastewater treatment systems, adapted from [9]
Rys. 4.2. Przemiany związków azotu w klasycznych układach oczyszczania ścieków, na podstawie [9]

The nitrification process involves a two-stage oxidation of ammonium nitrogen. In the initial stage, known as Nitritation, ammonium nitrogen is oxidised to nitrite. This step is primarily carried out by chemolithotrophic bacteria belonging to the genera *Nitrosomonas*, *Nitrosospira* or *Nitrosococcus*. In the subsequent stage, nitrite nitrogen is further oxidised to nitrates by chemoautotrophic bacteria from the genera *Nitrobacter*, *Nitrospira* or *Nitrococcus*. Simplified stoichiometrically, the two stages of nitrification can be expressed as follows [12, 13].

$$NH_4^+ + 1.5O_2 \rightarrow NO_2^- + H_2O + 2H^+ + energy \tag{4.1}$$

$$NO_2^- + 0.5O_2 \rightarrow NO_3^- + energy \tag{4.2}$$

The oxygen demand in the nitrification process is determined to be 4.57 grams of oxygen per gram of ammonium nitrogen (gO_2/gNH_4-N). It is important to note that the nitrification process also consumes alkalinity, which can potentially lead to a decrease in pH, particularly if the wastewater's buffering capacity is low. However, it is essential to understand that nitrification is solely the conversion of one form of nitrogen to another. The actual removal of nitrogen from wastewater occurs through the denitrification process. During denitrification, nitrate is sequentially reduced, first to nitrite, then to nitrogen oxides (NO and N_2O) and finally to gaseous nitrogen. This process allows for the complete removal of nitrogen from wastewater (as shown in equation 4.3).

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow 0.5N_2O \rightarrow 0.5N_2 \qquad (4.3)$$

The denitrification process is carried out by heterotrophic bacteria that require a carbon source. Therefore, an important parameter is the carbon-to-nitrogen ratio (C/N) or, more commonly used, the ratio of Chemical Oxygen Demand (COD) to nitrogen. The COD requirements for nitrate denitrification are 2.9 g COD/g NO_3-N; however, in practice the COD/N ratios for a satisfactory denitrification varied between 4 and 15 g COD/g N [14, 15, 16]. A commonly encountered challenge in the denitrification process is a low carbon-to-nitrogen (C/N) ratio, leading to reduced efficiency in nitrogen removal. To address this issue, a strategic approach involves placing the denitrification chamber upstream of the nitrification chamber and utilising nitrate recirculation to enhance denitrification efficiency. Alternatively, an external carbon source can be introduced (e.g. methanol, ethanol, glucose, or sodium acetate), although this significantly escalates the treatment costs [17, 18].

Wastewater treatment plants with population equivalent (PE) of over 100,000 individuals are subject to strict regulations, imposing stringent limits on the concentration of total nitrogen in treated wastewater discharged into the environment, which can be as low as 10 g N/m^3. These stringent limits have led to a situation where there is a deficiency of easily decomposable carbon in the raw wastewater, which is essential for the denitrification process. This becomes particularly critical during winter periods, characterised by low temperatures, when the denitrification chambers have limited capacity due to the necessity of conducting the nitrification process and maintaining a sufficiently long sludge age.

In addition to incoming wastewaters, sidestreams within the wastewater treatment plant, which are liquors derived from dewatering digested sludge, can contribute to the nitrogen load in the biological nitrogen removal process [19]. These reject water have a relatively high concentration of ammonium nitrogen (typically 200–700 g/m³) and a lower content of biodegradable organic matter. The HCO_3^-:NH_4^+ ratio in sludge water is typically 1.1:1 [19, 20].

Although the volumetric flow of reject water is only around 2%, it can contain up to 25% (or even more in the case waste co-digestion) of the total nitrogen load in the flow. This reject water is usually returned to the beginning of the waste treatment plant [19, 21, 22], which can be problematic, especially if there is limited capacity for aeration, nitrification and denitrification. Conventional biological extension would require additional aeration tanks, resulting in a significant investment [23, 24]. In some cases, modifying the operation of existing mainstream processes on-site may be a cost-effective option. However, for works where sidestreams contribute a significant proportion of the total ammonium loading on the mainstream processes, directly treating the sidestreams could be a viable solution [19].

Bioaugmentation

Nitrification is a crucial process in wastewater treatment plants as it determines the overall treatment rate. However, achieving low nitrogen concentrations in the plant effluent requires long sludge ages, particularly during winter periods. In conventional activated sludge systems with short sludge ages, nitrification is limited due to intense competition among heterotrophic bacteria and nitrifiers, among other factors [25]. Moreover, the nitrification potential of activated sludge systems is often restricted at lower temperatures (below 15°C), necessitating the construction of larger aeration chambers. Additionally, the denitrification process, which often requires even larger reactor capacities, needs to be carried out. However, during winter periods, the capacity of these chambers is reduced to prioritise enhancing the capacity of nitrification chambers. It is worth noting that activated sludge systems have low concentrations of nitrifiers, accounting for only 1–3% of the bacterial population [26]. Studies indicate that to ensure stable and efficient nitrification, the population of nitrifiers, including both ammonium oxidizing bacteria (AOB) and nitrite oxidizing bacteria (NOB), should represent 5 to 8% of the biomass [27]. Therefore, enhancing the nitrification capacity of the sludge by increasing the number of nitrifiers in the system is a reasonable approach [25]. Inoculation with nitrifiers is also advantageous when designing new treatment plants or upgrading the existing ones, as it enables the use of smaller reactors while maintaining the same loads by employing shorter sludge ages [28].

Several technologies utilise bioaugmentation of the mainline with nitrifiers, including InNitri (Inexpensive Nitrification) [29], BABE (Biological Augmentation Batch Enhanced) [30], BAR (Bioaugmentation Reaeration) [25], ScanDeNi [31] or MAUREEN (Mainstream Autotrophic Recycle Enabling Enhanced N-removal) [28], among others. This paper primarily focuses on the BABE technology.

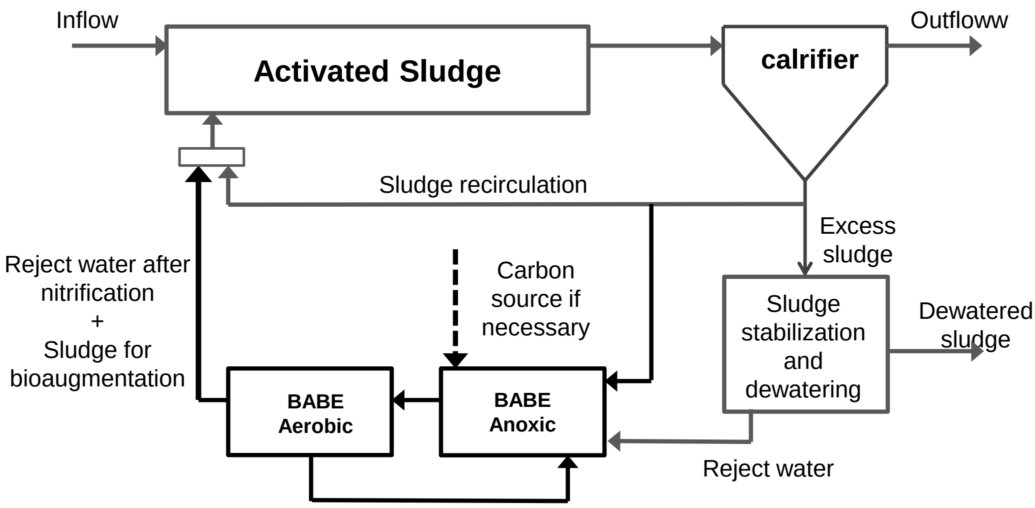

Fig. 4.3. Technological scheme of the BABE process, adapted from [30]
Rys. 4.3. Schemat technologiczny procesu BABE, na podstawie [30]

The BABE (Bio-Augmentation Batch Enhanced) process was developed to treat methane digestion reject water separately and return it to the main process line in wastewater treatment plants. This technology aims to enhance the efficiency of the activated sludge process by introducing nitrifiers in the form of sludge flocs, reducing the required sludge age and improving nitrification efficiency. Unlike the InNitri process, BABE also includes denitrification to control pH. By dosing a portion of the recirculated sludge, the need for an external carbon source for denitrification is minimised or eliminated. The BABE process utilizes endogenous transformation of recirculated sludge for supplying electrons in the absence of oxygen. Inoculating the main process line with autochthonous biomass is crucial, which is achieved by nitrifying sludge water with the addition of recycled sludge [32].

The BABE process can be implemented in one or two reactors. In a single-reactor system, the process occurs in cycles. During the aerobic phase, sludge water and recirculated sludge are introduced for nitrification. In the subsequent phase, denitrification takes place, followed by sludge sedimentation. The treated effluent is then directed to the main line of the treatment plant, and the nitrifiers present in the sludge inoculate the main process line due to incomplete sedimentation [28, 30]. The BABE process is an example of a technology that was initially developed based on simulation models and then directly implemented at full scale, bypassing laboratory tests (deemed unrepresentative) and pilot-scale trials (considered costly compared to full-scale trials).

Systems with bioaugmentation offer a very interesting alternative in the treatment of sludge water. In addition, by inoculating the main process line with nitrifiers and sometimes heterotrophic bacteria, the nitrogen removal capacity of the main treatment line is increased. However, despite the undoubted advantages of these systems, they have not gained widespread recognition, and full-scale installations are very few. In addition, this process is now being displaced by the partial nitrification/anammox process, which allows much greater savings.

Nitritation/denitritation

In both nitrification and denitrification, the intermediate product is nitrite. Stopping the nitrification process at the first stage and the subsequent denitrification from nitrite means that we can save about 25% of the oxygen demand and about 60% of the organic carbon demand. This additionally also results in a reduced biomass gain of up to about 40%. (Fig. 4.4) [30].

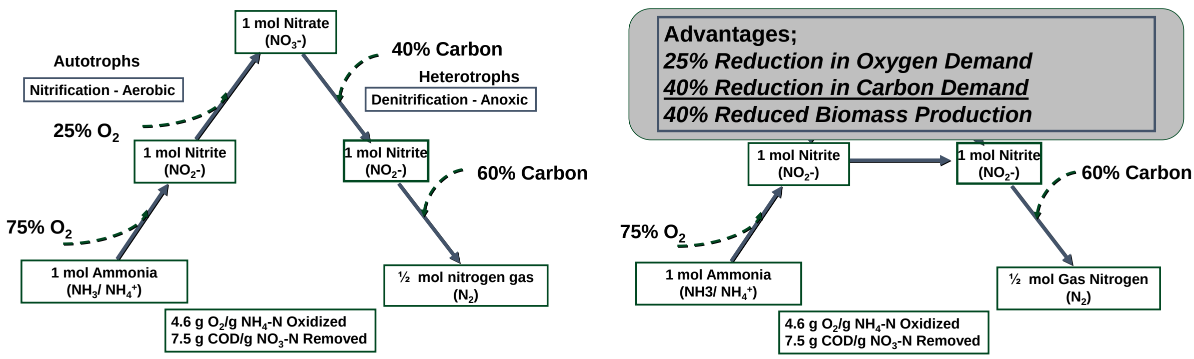

Fig. 4.4. Schematic comparing full nitrification/denitrification with nitritation/denitritation, adapted from [30]

Rys. 4.4. Schemat porównujący pełną nitryfikację/denitryfikację z nitritacją/denitritacją, na podstawie [30]

Different methods can be employed to control the growth of nitrite-oxidising bacteria and promote the proliferation of ammonium nitrogen-oxidising bacteria. One approach capitalises on the temperature-dependent variations in the growth rates of these bacterial groups, achieved through measures like reducing dissolved oxygen levels or inhibiting them with free ammonia (NH_3) or free nitric acid (HNO_2). An example of such a process is the SHARON (Single reactor High Activity Ammonia Removal Over Nitrite) process [34]. This method focuses on restricting the second stage of nitrification. It involves aerobic oxidation of ammonia nitrogen to nitrite, followed by anoxic reduction of nitrite to gaseous nitrogen using an external carbon source. The second stage of nitrification is constrained by employing a very short hydraulic retention time and maintaining a high temperature that causes the nitrite-oxidising bacteria to flush out of the system. A temperature of 30–40°C is maintained in the reactor since at temperatures above 20°C, the growth rate of ammonium-oxidising bacteria exceeds that of nitrite-oxidising bacteria (Fig. 4.5) [9, 12, 35].

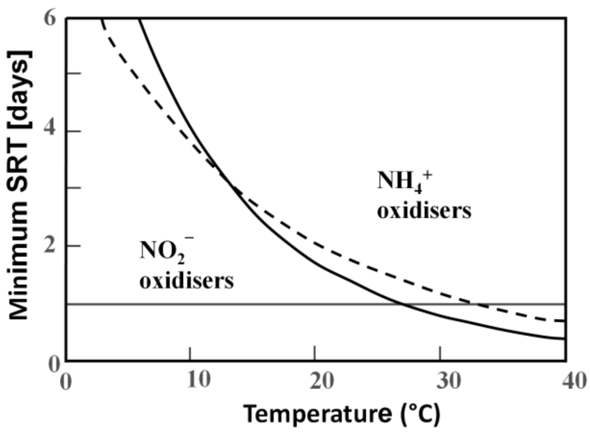

Fig. 4.5. Minimum sludge retention time (SRT) for ammonium and nitrite oxidisers at different temperature, adapted from [35]
Rys. 4.5. Minimalny czas zatrzymania osadu dla bakterii utleniających azot amonowy i azotynowy w różnych temperaturach, na podstawie [35]

The SHARON process has been implemented on a full scale in the Netherlands at the Dokhaven WWTP, among others. However, the discovery of the anammox process in the late 1990s completely revolutionised the nitrogen removal from sludge water and the approach to modern wastewater treatment.

Partial nitritation/anammox process

Traditional nitrification and denitrification processes are effective for treating typical municipal wastewater. However, certain nitrogen-rich wastewaters, such as landfill leachate, sludge water from digested sludge dewatering or industrial wastewaters, pose challenges for these conventional processes. These challenges arise due to the inhibition of the process by free ammonia and the insufficient biodegradable carbon content required for denitrification. Treating nitrogen-rich wastewater using nitrification and denitrification becomes economically impractical due to the high oxygen demand (which accounts for about 60–70% of total energy consumption in a wastewater treatment plant) and the need for an external carbon source.

To address these issues, partial nitrification/anammox technology has emerged as a less energy-intensive alternative for converting ammonium nitrogen into gaseous nitrogen. This technology offers several advantages over conventional nitrification and denitrification processes. It reduces sludge production, lowers aeration costs by nearly 60% (as only half of the ammonia is oxidised to nitrite without further oxidation to nitrate) and eliminates the need for an external source of organic carbon (anammox process). Furthermore, during anammox, ammonium nitrogen is oxidised under anoxic conditions using nitrite as an electron acceptor, and the energy generated is used for CO_2 fixation. This is crucial, as future regulations may impose limits on greenhouse gas emissions, and energy consumption metrics, such as kilowatt-hour per million cubic meters (kWh/Mm^3) or per capita, will become integral to the water sector's operations. Consequently, potential CO_2 taxes could significantly impact costs in the future. The anammox process reduces CO_2 emissions by 90% compared to nitrification and denitrification. Hence, it offers an appealing alternative to traditional nitrification and denitrification for wastewater management [36, 37].

Additionally, the anammox process has a very low biomass yield (0.08 kg VSS/kg NH_4-N) compared to conventional nitrification and denitrification (1 kg VSS/kg NH_4-N). This results in minimal sludge production, further contributing to lower operating costs compared to conventional denitrification systems. However, efficient sludge retention is necessary due to the low biomass yield [38].

In the anammox process, ammonium is converted to dinitrogen gas with nitrite as electron acceptor in a ratio 1:1.32 [39] (eq. 4.4).

$$NH_4^+ + 1{,}32NO_2^- + 0{,}066HCO_3^- + 0.13H^+ 1{,}02N_2 + 0.26NO_3^- + 0.066CH_2NO_{0.5}N_{0.15} + 2.03H_2O \quad (4.4)$$

The primary outcome of anaerobic ammonia oxidation is the production of dinitrogen gas. However, approximately 10% of the nitrogen present in the influent is converted into nitrates. The overall nitrogen balance demonstrates a ratio of ammonium to nitrite to nitrate of approximately 1:1.32:0.26. anammox bacteria exhibit a remarkably high affinity for their substrates, ammonium and nitrite. The affinity constant values for ammonium and nitrite are below 5 μM [40]. The anammox process relies on nitrite as an electron acceptor for the anaerobic oxidation of ammonium. In wastewater treatment applications, various setups are employed to supply nitrite, including single reactor and two reactor systems. The common objective in all these systems is to provide anammox bacteria with nitrite [40]. Typically, a portion of the ammonium is converted to nitrite, and then the remaining ammonium, along with the generated nitrite, is further converted to dinitrogen gas by anammox bacteria. In addition, for some specific wastewater it is possible to combine the anammox process with denitrification using sulphide as an electron donor to produce nitrite from nitrate [41]. Figure 4.6 illustrates the anammox process in different configurations and for different nitrite sources [11].

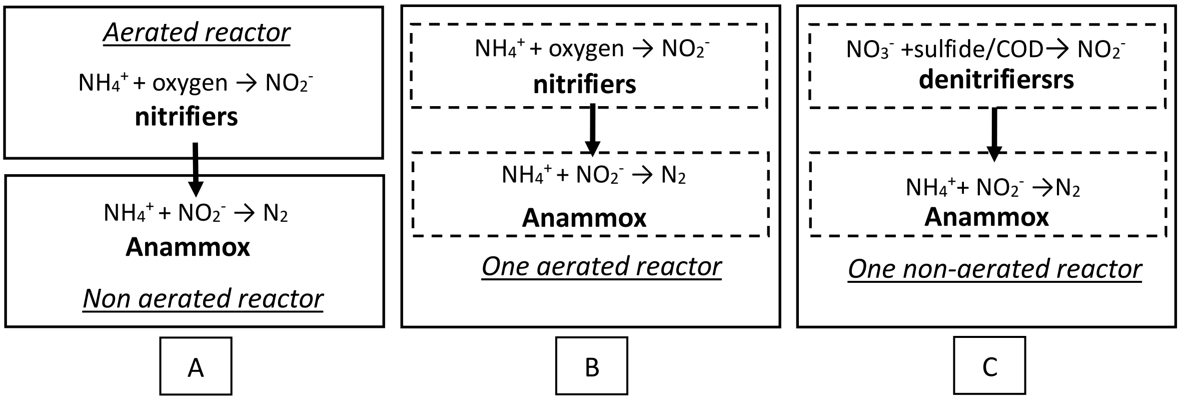

Fig. 4.6. Simple scheme illustrating different Anammox configuration and different source of nitrite: A) Nitritation and Anammox in Two-reactors in a series, B) Nitritation and Anammox in one single reactor, C) Partial denitrification of nitrates to nitrites with the Anammox process in one non-aerated reactor, adapted from [9, 11]

Rys. 4.6. Schematyczne przedstawienie możliwych połączeń procesu anammox z różnymi sposobami produkcji azotanów (III): A) częściowa nitryfikacji i anammox prowadzone w dwóch osobnych reaktorach, B) częściowa nitryfikacja i anammox prowadzone symultanicznie w jednym reaktorze, C) częściowa denitryfikacja azotanów (V) do azotanów (III) połączona z procesem anammox [9, 11]

The practical application of the anammox process has become widespread in various technical installations. Over the years, there has been a significant growth in the number of full-scale plants worldwide employing the anammox process. The first implementation was reported in 2002 and, by 2008, there were already 5 installations. Recent data indicates that the number of facilities has surpassed 200, highlighting the increasing adoption of this process [42, 43, 44, 45]. Despite the considerable expansion of treatment plants, their predominant focus remains on treating wastewater with high nitrogen loading, low organic loading, and temperatures above 25°C [34].

4.3.2. Phosphorus removal

Similar to nitrogen, phosphorus is a biogenic element essential for the growth of aquatic life. However, excessive discharge of phosphorus into water bodies leads to the excessive growth of algae. When these algae die, they release organic pollutants that require additional oxygen for decomposition. This process results in a decrease in oxygen concentration in the water, leading to the death of organisms and causing secondary pollution due to the increased load of organic compounds and nutrients. To mitigate this issue, one approach is to enhance the efficiency of wastewater treatment and utilise highly effective methods for removing nitrogen and phosphorus [9]. The elimination of phosphorus from wastewater can be achieved through various approaches, including physico-chemical methods, biological treatment, or a combination of both. Many well-established large-scale techniques are available for this purpose [46].

Chemical phosphorus removal

In the past, the addition of chemical compounds like lime and iron (II) sulfate to wastewater was a way to remove suspended solids and organic compounds when biological treatment was not very advanced. Today, biological wastewater treatment is dominant, but chemical treatment is very often used to eliminate phosphorus from wastewater [46]. The commonly used chemical methods for phosphorus removal often involve adding metal salts to the influent of pre-treated wastewater, conventional activated sludge (CAS) reactors, or the effluent from the secondary clarifier [47]. The following reactants are most commonly used in chemical precipitation and coagulation processes [9]:

- Calcium oxide or calcium hydroxide, CaO or $Ca(OH)_2$,
- Aluminium sulfate, $Al_2(SO_4)_3$ $18H_2O$,
- Iron(III) chloride, $FeCl_3$,
- Iron(II) sulfate, $FeSO_4$,
- Iron(III) sulfate, $Fe(SO_4)_3$.

In the chemical removal of phosphates, multiple processes occur simultaneously. These processes include the precipitation of phosphates as insoluble precipitates, the adsorption of phosphate on the surface of partially oxidised colloidal oxides and hydroxides, and the coagulation of precipitated particles. According to suggestions made by [48], the amount of salt needed to achieve the desired phosphorus removal rate may exceed the stoichiometric ratio by up to double due to several bi-reactions.

Adsorption of phosphorus from wastewater

The utilisation of chemical adsorption for phosphorus removal is steadily gaining popularity. Phosphorus adsorption allows for the potential desorption of phosphorus from the material, enabling the recovery of phosphate from wastewater. A wide range of materials can serve as sorbents for this adsorption process, including but not limited to metal oxides and hydroxides, furnace slag, fly ash, and chemically modified clays. Ongoing extensive research focuses on identifying the most cost-effective and efficient material for phosphorus removal from wastewater [49]. However, many of these sorbents are expensive and/or may cause some environmental problems. In recent years, biochar, as an economical and environmentally friendly sorbing material, has received much attention and has been used as a novel sorbent for the removal of different organic and inorganic pollutants. Biochar is a type of sustainable carbonaceous material that is produced from the thermal treatment of agricultural organic residues and other organic waste streams under oxygen free conditions. Many studies have shown that the development of the structure and surface area of biochar can improve P sorption capacity by providing sufficient space for the interaction of P and biochar surfaces [50].

Biological phosphorus removal

The method of removing phosphorus, along with excess sludge, is severely limited due to the very small amount of phosphorus present in the organic fraction of the sludge (0.023). However, it is possible to increase the phosphorus content in activated sludge by leveraging the properties of specific organisms and modifying the activated sludge process. This can be achieved by implementing alternating anaerobic and aerobic conditions (refer to Figure 4.7). Enhanced Biological Phosphorus Removal (EBPR) is a technique that utilises polyphosphate-accumulating organisms (PAO) to eliminate phosphate from wastewater and convert it into sludge in the form of intracellular polyphosphate. These PAOs have the capacity to absorb more phosphorus than required for their growth. Through the EBPR process, it is possible to remove over 85% of phosphorus from wastewater. During anaerobic conditions, bacteria assimilate dissolved readily available organic substrates (volatile fatty acids or VFAs) and convert them into an endogenous reserve substance called poly-β-hydroxybutyrate (PHB). This conversion occurs at the expense of energy released during polyphosphate decomposition, which results in the release of phosphate into the environment. Under aerobic conditions, the stored PHB and organic matter obtained from the environment undergo oxidation. Part of the energy obtained from this process is stored as polyphosphates, while simultaneously absorbing phosphates from the environment in quantities greater than those previously released [9, 49].

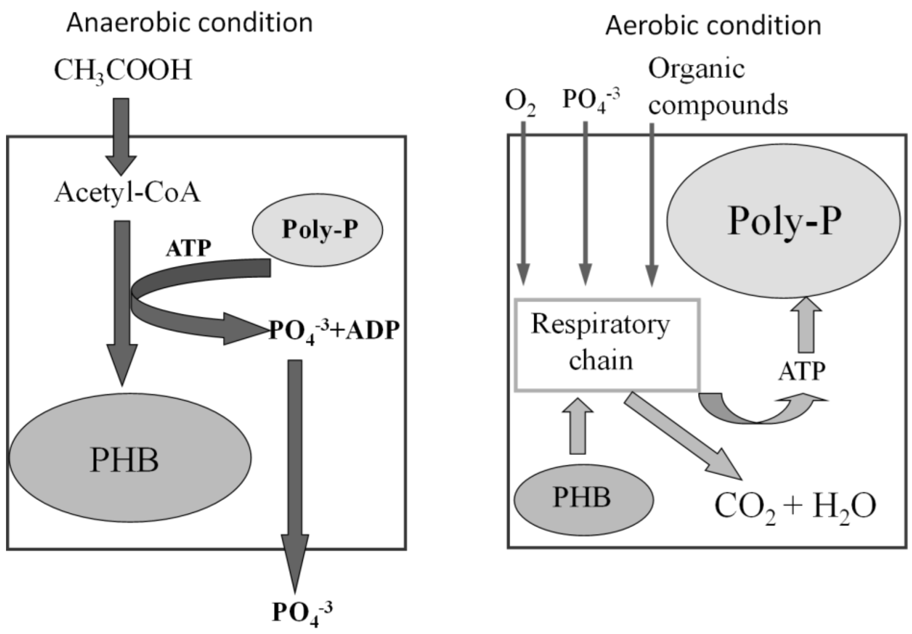

Fig. 4.7. Metabolic pathways of PAO under aerobic and anaerobic conditions, adapted from [9]
Rys. 4.7. Szlaki metaboliczne PAO w warunkach tlenowych i beztlenowych, na podstawie [9]

Integrate nitrogen and phosphorus removal

In order to comply with current legal standards, wastewater treatment plants are required to remove both nitrogen and phosphorus, as well as achieve high treatment efficiency in terms of suspended solids and organic compound removal. To accomplish this, various technological systems are employed for the removal of carbon (C), nitrogen (N) and phosphorus (P). These systems typically incorporate an anaerobic chamber at the beginning of the treatment process, where the initial phase of biological phosphorus removal takes place. The placement of the anaerobic chamber is designed to ensure the availability of easily degradable organic compounds, which are necessary for the implementation of the biological phosphorus removal process. The subsequent arrangement of chambers is focused on facilitating denitrification, nitrification, and the second phase of biological phosphorus removal. Some commonly used systems include the Bardenpho system or the A2/O system (refer to Figure 4.8).

These systems are comprised of an anaerobic chamber, an anoxic chamber and an aerobic chamber, that are interconnected in a series. The anaerobic chamber serves as the starting point for the biological phosphorus removal process, receiving both raw wastewater and recirculated sludge. In the subsequent anoxic chamber, biological denitrification occurs by treating the nitrates returned through the internal recirculation stream. In the aerobic chamber, nitrification of ammonium nitrogen takes place, along with the second phase of biological phosphorus removal.

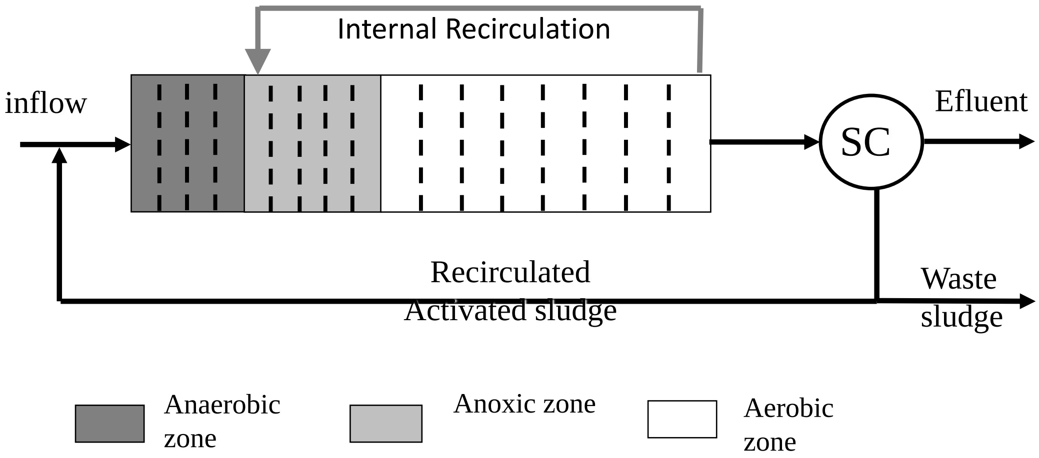

Fig. 4.8. Scheme of A2/O system (SC – secondary clarifier), adapted from [9]
Rys. 4.8. Schemat technologiczny systemu A2/O (SC – osadnik wtórny), na podstawie [9]

Efforts to enhance nutrient removal efficiency have resulted in modifications to these systems, such as the 5-stage Bardenpho system or the MUCT system (refer to Figure 4.9). These modified systems incorporate an additional internal recirculation system to prevent nitrates, which would decrease the efficiency of biological phosphorus removal, from entering the anaerobic chamber [9, 51].

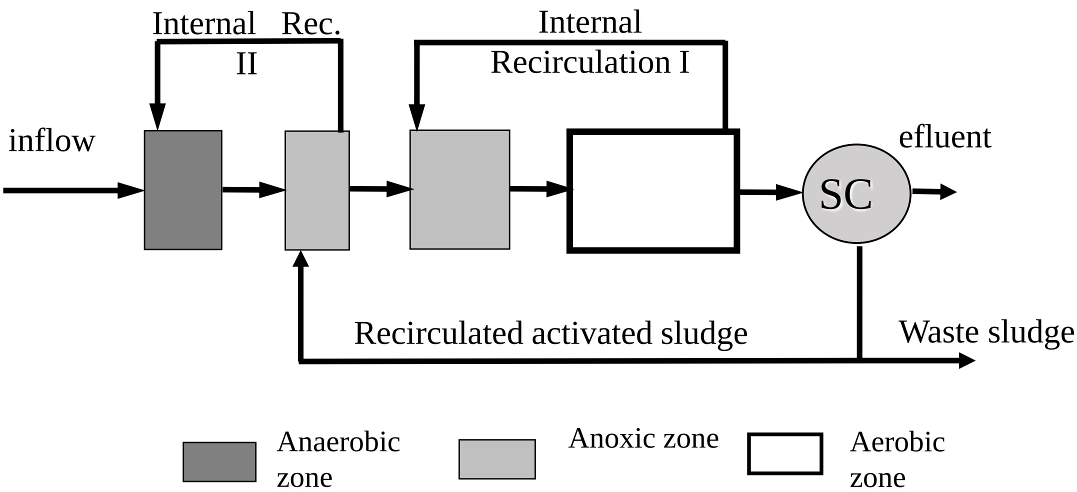

Fig. 4.9. Scheme of MUCT system (SC – secondary clarifier), adapted from [9]
Rys. 4.9. Schemat technologiczny systemu MUCT (SC – osadnik wtórny), na podstawie [9]

4.3.3. Nutrients recovery

The concept of resource recovery has been discussed for many years. However, since the beginning of the 21st century, there has been a growing recognition of resource scarcity, which has led to an increased emphasis on this approach. The focus is on maximising the potential for recovering valuable resources from wastewater treatment processes. This shift aims to enhance the efficiency and sustainability of wastewater treatment while also addressing the need for resource conservation [52].

Initially, there has been a considerable focus on the recovery of phosphorus due to its status as a valuable and strategic raw material. The most straightforward approach to phosphorus recovery from sludge involves utilising activated sludge directly as a fertiliser. However, the transportation and handling of highly hydrated sludge (typically above 50% H_2O) can contribute to a significant portion, ranging from 25% to 65%, of the total operational costs of a treatment plant [53].

The integration of phosphorus recovery into wastewater treatment processes offers the opportunity to separate dissolved phosphorus using relatively simple technologies. This allows for the extraction of phosphorus-rich side streams or process water with phosphorus concentrations exceeding 50 g/m^3, which can be economically beneficial. One significant advantage of phosphorus recovery during wastewater treatment is the possibility of combining it with phosphorus removal. Recent investigations have demonstrated that the most successful outcomes are achieved when combining phosphorus recovery with biological phosphorus removal in side streams (such as supernatant liquor from the anaerobic stripper) or during sludge treatment in process water. The phosphorus-rich water is directed into a precipitation/crystallisation tank, where calcium or magnesium salts, along with seed crystals if necessary, are added. This facilitates the removal of phosphorus as calcium phosphate or magnesium ammonium phosphate (struvite) through the precipitation process [54]. There are also physical recovery processes based on ion exchange, adsorption and membrane systems that are being used to recover nutrients from wastewater. One of their applications is the recovery of ammonia, nitrate or phosphates for the treatment of secondary effluent through adsorption by ion exchange [52]. Another possibility is phosphorus recovery as vivianite, which is primarily found in digested sludge, has emerged as an innovative method that has garnered considerable attention. This process offers several advantages, including the natural abundance of vivianite, its accessibility and the potential for economic value. However, it is important to note that this method is still in its early stages of development, and further research is needed to fully understand and optimise its potential [52]. According to the findings of Cieślik and Konieczka [53], recent literature suggests that phosphorus recovery efforts should prioritise the utilisation of ash derived from the incineration of sewage sludge. Currently, there is a greater volume of literature available on phosphorus recovery from sludge through thermal processes compared to recovery from sewage and leachates. This indicates that research and attention have predominantly focused on exploring phosphorus recovery from sludge incineration rather than from other sources.

Recovering a pure or highly concentrated ammonia stream can be completed with physical/chemical methods: air stripping, steam stripping, hollow fibre membrane contactors, and struvite precipitation. These methods are the most cost effective at high initial ammonia concentrations and hence only useful on side-stream effluents or source-separated urine [13].

4.4. Micropollutants

Micropollutants refer to biologically active and persistent substances found in the aquatic environment at low concentrations (typically in the ng and μg/l range). These substances can have detrimental effects on humans, the environment and drinking water resources. Examples of micropollutants include pharmaceuticals, personal care products, pesticides and perfluoroalkyl substances. While some of these substances end up in municipal wastewater, and subsequently enter wastewater treatment plants, these facilities are not designed to effectively eliminate micropollutants. Only a few are successfully removed, such as ibuprofen and its metabolites, while others like carbamazepine are not broken down during the biological treatment process and are released into surface water. The European Commission is currently considering a proposal for a new Urban Wastewater Treatment Directive (91/271/EEC) [55], which aims to make the application of a fourth stage of wastewater treatment mandatory. This fourth stage would specifically target the removal of a wide range of micropollutants. Additionally, an updated version of the Water Framework Directive (2000/60/EC) [56] is being prepared. The revised directive will expand the range of priority substances used to assess water quality, surpassing the current list of 33 chemicals. Moreover, it is expected to introduce a "watch list" that includes 23 substances requiring a specific analysis in environmental waters. The requirement for implementing the quaternary urban wastewater treatment stage will apply to agglomerations with a capacity of over 100,000 population equivalents (PE). It will also be mandatory for agglomerations with a capacity of 10,000 to 100,000 PE if surface water protection necessitates it. This includes ensuring good water status according to the Water Framework Directive, maintaining bathing water quality, safeguarding water abstraction areas for drinking water production, and addressing areas with limited dilution for discharged wastewater into low-water recipients. However, the introduction of this fourth stage of wastewater treatment will pose significant challenges for water and wastewater utilities, comparable to the previous adoption of uniform European requirements for urban wastewater treatment (Directive 91/271/EEC). It will undoubtedly require substantial investments and lead to high operating costs, especially when combined with the demand for reduced energy consumption in wastewater treatment plants.

4.5. Future of the Wastewater Treatment Plant – the biorefinery concept

4.5.1. Wastewater treatment plant – towards energy neutrality

Energy neutrality in treatment plants has become one of the most popular points of discussion in the field of sustainability of the activated sludge [57]. Treatment and transport of wastewater currently consumes approximately 4% of the total electrical power produced in the US. In Europe, WWTPs contribute to approximately 1% of the total electricity consumption in the cities [58]. This elevated energy usage is attributed to both the escalating costs of electrical energy and the impact it has on the treatment process's carbon footprint. In the realm of municipal wastewater treatment, the activated sludge process is widely employed, particularly in centralised facilities. However, this conventional method can account for up to 60% of the overall power requirements of a treatment plant due to the aeration necessary in the biological tank. One approach to mitigate this high energy demand is by minimising the reliance on aeration whenever possible. By doing so, not only can energy consumption be reduced, but the carbon footprint can also be diminished, providing an additional environmental benefit [59]. To attain energy self-sufficiency in wastewater treatment plants, the primary objective should be to minimise energy consumption, particularly in aeration, while maximising energy recovery from the pollutants present in wastewater. Several measures can be implemented to achieve energy neutrality, including:

- Reducing energy consumption in wastewater treatment processes.
- Enhancing energy recovery from internal sources within the treatment plant.
- Incorporating ample external sources of renewable energy.

By implementing these measures, wastewater treatment plants can work towards energy neutrality, where the energy consumed is offset by energy generated or recovered within the system [58].

The implementation of the partial nitrification/anammox process to remove nitrogen from reject water in a sidestream offers several advantages. It has the potential to reduce the need for aeration in the treatment plant and also allows for the possibility of reducing denitrification without compromising nitrogen removal efficiency. As a result, this process enables increased removal of organic matter during pretreatment, leading to higher biogas production. Ultimately, these improvements contribute to the plant's progress towards achieving energy neutrality [60]. To illustrate this, two municipal wastewater treatment plants (WWTPs) in Austria, namely Strass TP and Wolfgangsee-Ischl TP, serve as examples. These plants have undergone a continuous optimisation process aimed at improving their performance. Optimisation measures include implementing optimal aeration control and effectively managing the aerobic section of the aeration tank. This allows for the optimisation of denitrification and prevents the degradation of particulate organic matter, which should instead be degraded in the digester. At Strass WWTP, the removal of nitrogen from reject water is achieved through the partial nitritation/anammox process, also known as deammonification. Additionally, the biogas produced in the digester is utilised in conventional CHP (Combined Heat and Power) units with an electrical efficiency close to 40%. The energy balance of the Strass WWTP is illustrated in Figure 4.10, demonstrating the successful integration of energy-efficient practices and the utilisation of biogas to enhance the overall energy performance of the plant [61, 62].

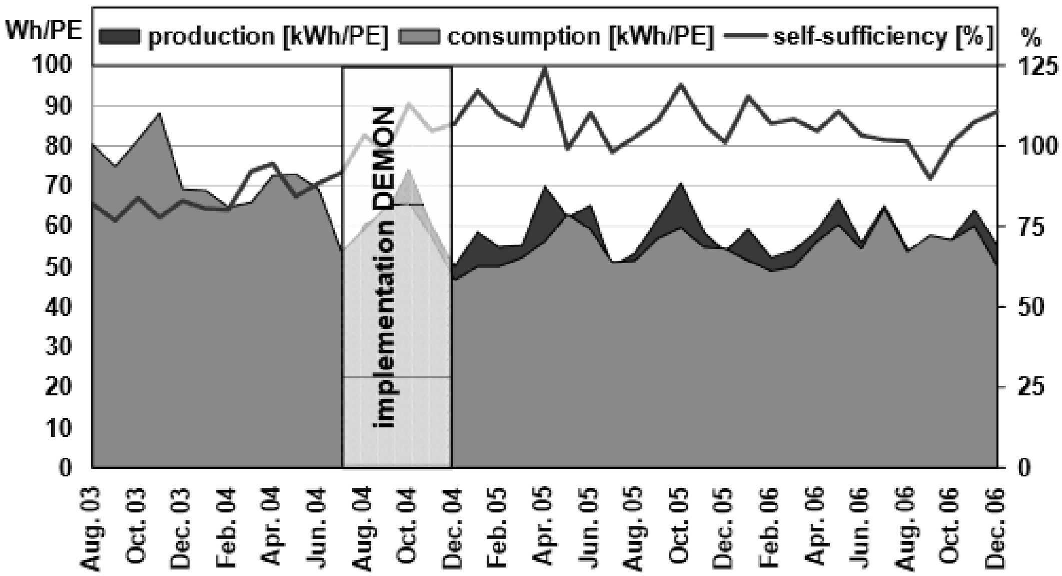

Fig. 4.10. Percentage of plant-wide energy self-sufficiency as the difference of demand and production of electrical energy after implementation of deammonification [61]

Rys. 4.10. Procent samowystarczalności energetycznej całego zakładu jako różnica zapotrzebowania i produkcji energii elektrycznej po wdrożeniu deamonifikacji [61]

4.5.2. The Biorefinery concept

Advancements in wastewater treatment and recovery technology have brought about a shift in how wastewater is perceived. It is no longer seen merely as a "waste" but rather as a valuable resource containing water, energy and useful substances. The future of municipal wastewater reclamation lies in adopting a next-generation biological process that moves beyond the traditional focus on simple removal. Instead, there should be a transition towards a synergetic approach that emphasises the recovery of water resources and power, harnessing the full potential of wastewater as a valuable resource [63, 64].

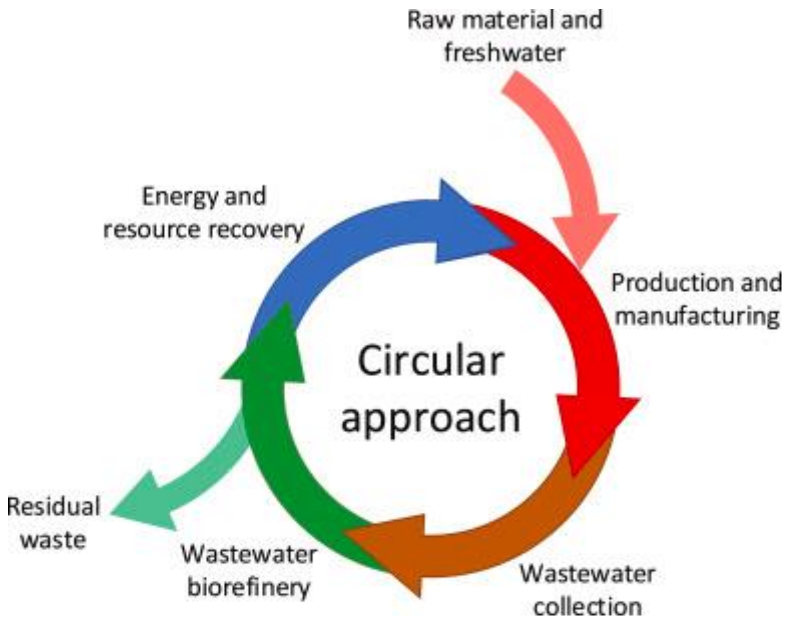

Fig. 4.11. Integration of circular approach into wastewater management [64]
Rys. 4.11. Oczyszczalnia ścieków jako fabryka dla wody, energii i zasobów [64]

It is necessary to maximise the utility of all the compounds present in wastewater and to return them to the economy. The wastewater biorefinery (WWBR) can meet this demand by eliminating waste and operating within a closed-loop economy (see Figure 4.11). In this way, the latest generation of WWTPs can supply energy, material and reclaimed water to the production and manufacturing processes and thus limit the need for raw materials and freshwater [64].

Wastewater treatment is embracing circular sustainability by incorporating energy production and resource recovery alongside clean water production. Microbial biotechnology perform a crucial role in this progress, as microbial communities can carry out essential processes such as carbon, nitrogen, phosphorus and micropollutant removal or reuse, as well as bioenergy and high-value product generation. Future challenges involve optimising existing systems, reducing chemical usage, minimising energy inputs, improving process stability, and exploring new approaches. These advancements contribute to achieving Sustainable Development Goal 6, ensuring accessible and sustainable water and sanitation, and Goal 7, providing affordable, reliable and sustainable energy access [65].

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5. SUSTAINABLE WASTE MANAGEMENT

12 Sustainable Development Goals (SDG 12) focus on sustainable consumption and production, which signifies the need to try to reduce wasting raw materials, increase the use of renewable sources of energy and limit the negative impact of production and consumption on the natural environment (Fig. 5.1). The waste is a key element of these goals because its amount and management method affect many aspects of sustainable development.

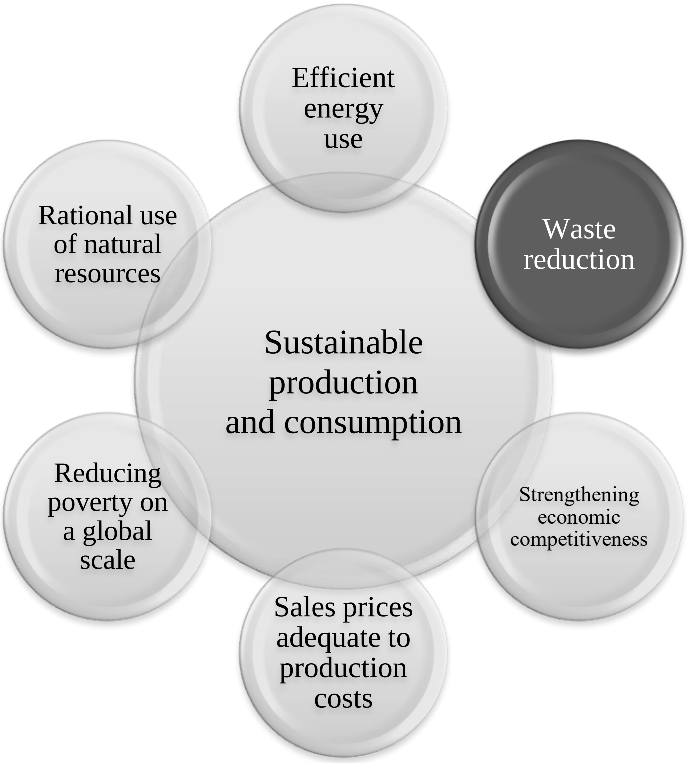

Fig. 5.1. Key elements of sustainable production and consumption [1]
Rys. 5.1. Kluczowe elementy zrównoważonej produkcji i konsumpcji [1]

A decrease in the amount of produced waste is crucial to achieving sustainable development goals. Producing excessive amounts of waste leads to the overuse of natural resources and the consumption of energy. That is why it is important to promote a more sustainable lifestyle in which we decrease our consumption, use products more efficiently and choose more environment-friendly options.

Another important element in the context of waste is its appropriate management. Landfills are the least desirable method of waste management, which is why it is important to apply alternative methods of waste management, such as recycling, composting or waste energy recovery. An improvement in waste management has a positive impact on environmental protection, improves the efficiency of the use of natural resources, reduces climate changes and the emission of greenhouse gasses as well as contributes to the improvement of people's quality of life.

In the context of the Circular Economy, waste is treated as secondary raw material and its minimisation is one of the key goals. The circular economy is based on three principles – "Reduce, Reuse, Recycle". It means that the amount of produced waste should be decreased by, for example, designing products with the idea that they will be reused or processed in the future. It is also important to prevent the wastage of materials through their recovery and reuse in production. In the circular economy, waste is treated as a valuable raw material and not useless waste. This increases the efficiency of the use of natural resources and contributes to environmental protection and the decrease in greenhouse gases emission.

The adoption of a new waste management model, supported by technological progress in key sectors, such as mobility, food and the environment, has the potential to generate significant economic and environmental benefits. It is estimated that in the European Union, where these sectors account for 60% of household budgets and consume 80% of resources, the introduction of a circular economy could result in an annual increase in resource productivity of up to 3%. This, in turn, would lead to a 7% increase in GDP compared to baseline forecasts [2].

The positive effects of a circular economy go beyond economic growth and have a significant impact on employment. Additionally, adopting circular practices would contribute to a further 10% reduction in resource consumption and a significant decrease in greenhouse gas emissions by 17%. The cumulative benefits of these actions are substantial, with estimated annual profits amounting to 1.8 trillion euros. They include both direct savings of 0.6 billion euros related to primary resource costs and 1.2 trillion euros of external benefits unrelated to resources [2].

Furthermore, transitioning to a circular economy would also have a positive impact on disposable household income in the EU, increasing it by 11% by 2030. This significant growth in disposable income would improve the well-being and quality of life of individuals and families throughout the European Union [2].

5.1. Rational waste management

Constant economic development and the worldwide increase in consumption result in the production of large amounts of waste. Each year, throughout the world more than 2.1 billion tons of municipal waste is generated. Only 16% of this waste undergoes recycling and 46% of the waste is deposited [3]. It is estimated that the amount of waste will increase with the expansion of the world population and above others with the raise of welfare. According to the World Bank, in 2016–2050 the amount of waste will increase by about 70%. Wastes, especially municipal wastes, are considered a global problem as they are visible and have a complex nature. Their morphological composition depends on the development of civilisation, the life quality and the welfare of a given society. An important impact on the form and mass of the generated municipal waste have such factors as the density of population, type of housing (single-family, multi-family housing) touristic attractiveness, public service buildings and type and size of commercial buildings. Every year the increase in collected waste is noted. As observed, richer countries usually produce about 34% of the world's waste, although they embrace about 16% of the population. The United States and Denmark are countries which generate the most waste per inhabitant [3]. On average, the inhabitants of these countries in 2022 produced over 800 kg of waste (Fig. 5.2).

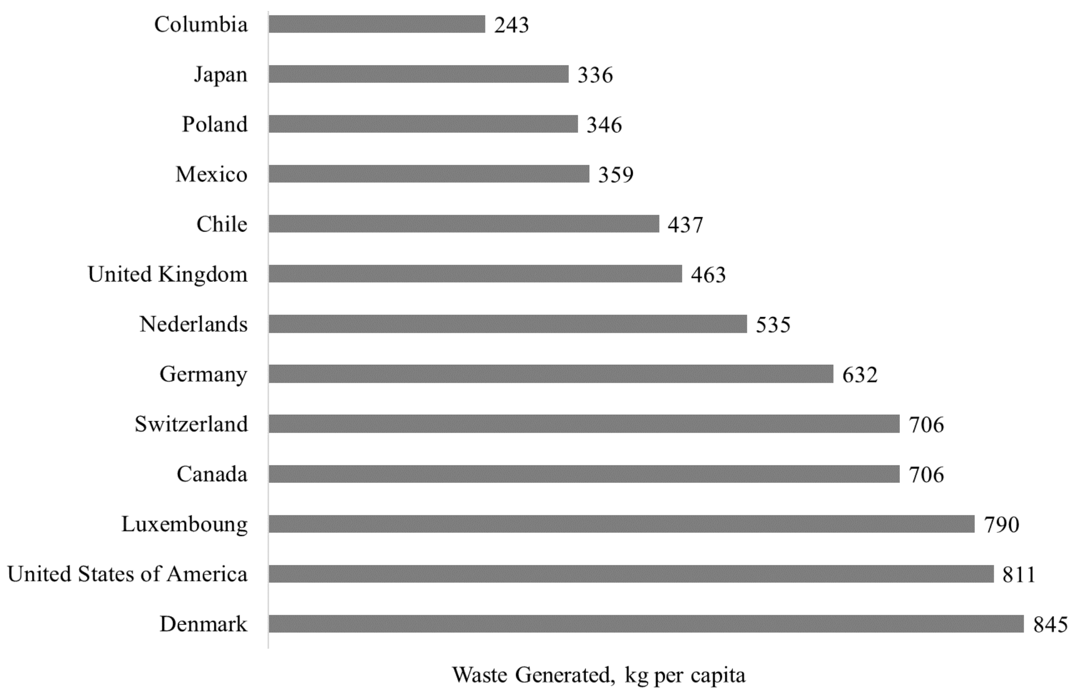

Fig. 5.2. Average annual per capita municipal waste generated [3]
Rys. 5.2. Średnioroczne wytwarzanie odpadów komunalnych [3]

The average amount of produced municipal waste per inhabitant of the European Union in 2021 was 530 kg. It increased by about 4.9% in comparison with the year 2020. The largest amount of waste was generated by counties of significant welfare: Austria – 834, Denmark – 814, Luxemburg – 790 and countries with a large participation of tourists, such as Malta – 643 or Cyprus – 609. The data presented in Figure 5.3. show that the amount of municipal waste per inhabitant of Poland (346 kg) was lower than the average in the EU and was one of the lowest. A lower amount of the generated municipal waste was noted only in Romania – 287 kg per inhabitant [4].

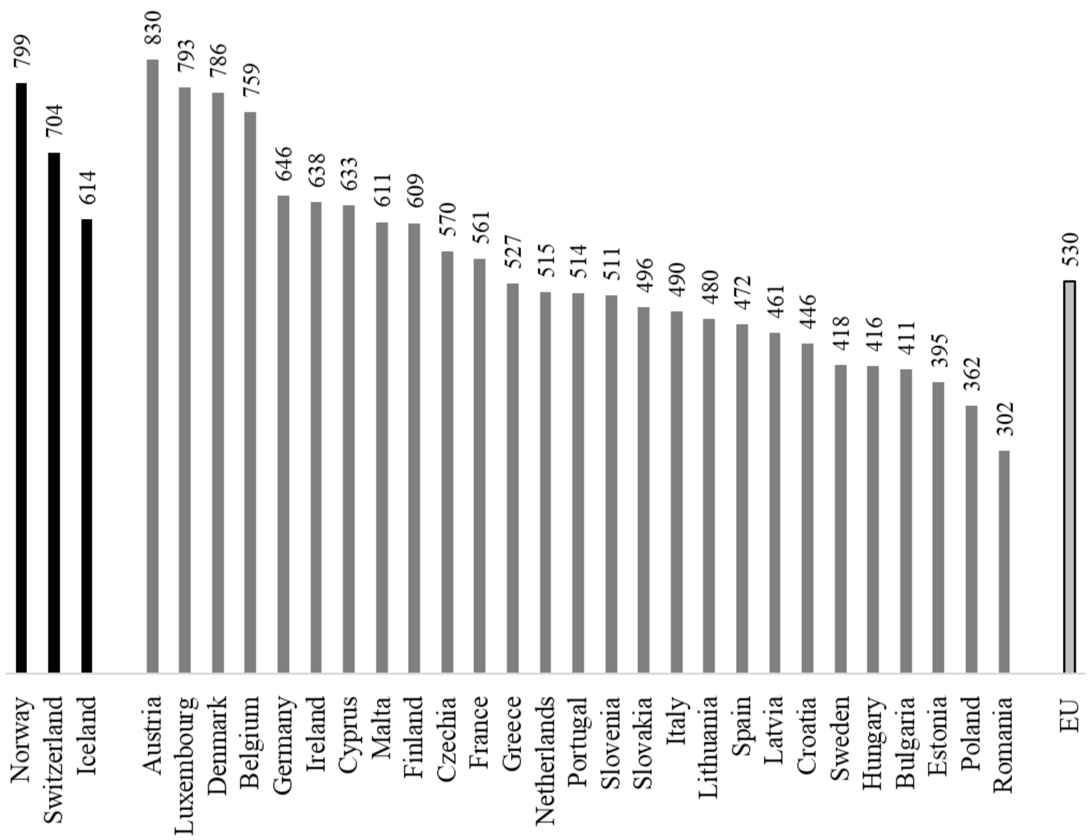

Fig. 5.3. Municipal waste generated in Europe, in 2021 (kg per capita) [4]
Rys. 5.3. Strumień odpadów komunalnych wytworzonych w Europie w 2021 (kg na mieszkańca) [4]

In Poland, in 2021 362 kg were produced per capita which is an increase of 4.6% as compared to the previous year. Although Poland has one of the lowest indexes among European countries, we are becoming a more consumptive and waste-producing society [5].

The largest amount of municipal waste was collected in Mazovian Voivodship (1971 thousand tons), Silesian Voivodship (1795 thousand tons), Greater Poland Voivodship (1297 thousand tons), Lower Silesian Voivodship (1262 thousand tons); the lowest amount was noted in Świętokrzyskie Voivodship (328 in thousand tons), Podlaskie

Voivodship (351 thousand tons) and Opolskie Voivodship (378 in thousand tons) (Fig. 5.4) [5].

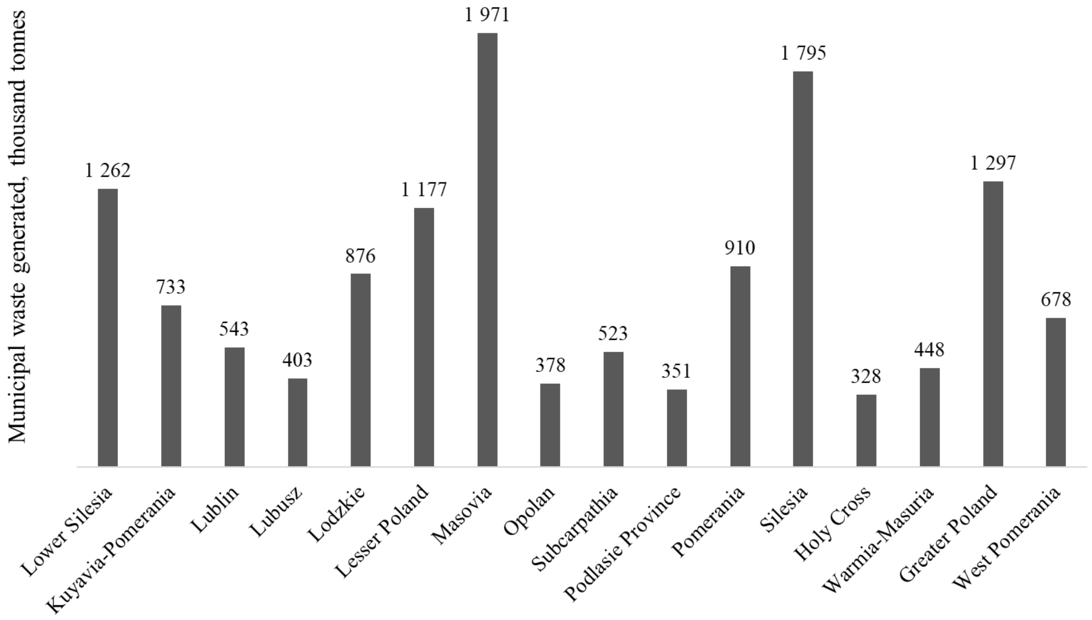

Fig. 5.4. Municipal waste generated by voivodships in 2021 [5]
Rys. 5.4. Odpady komunalne wytworzone według województw w 2021 [5]

5.1.1. Waste management hierarchy

Nowadays, in the EU countries, an increasing stream of municipal waste is one of the most important challenges in the area of environmental protection and legal requirements The waste directive 2008/98/WE specifies a waste management hierarchy: Reduce, Reuse, Recycle, Recover and Disposal [6]. The hierarchy aims to eliminate waste with the minimum damage to the health and environment (Fig. 5.5). The hierarchy is a tool which makes it possible to create a modern and integrated waste management economy. One may say that the actual hierarchy is limited because it only accounts for the environmental aspect. It does not take into consideration social, economic or logistic aspects, which are costly and aggravating to the environment. According to the binding hierarchy, in the first place, it is recommended to prevent the generation of waste. Then, the waste should be prepared for reuse and undergo recycling or other recovery processes, including energy recovery. The last stage of waste management is their neutralisation by, for example, depositing [6, 7].

The valid hierarchy orders waste management methods but does not bring Europe closer to the circular economy and sustainable development. The strategic aim of the EU is to preserve the resources for future generations. In order to achieve this goal, new tools are necessary. A solution which will enable achieving a circular economy and climatic neutrality in Europe is reshaping the hierarchy into the Zero Waste one [7, 8]. The new hierarchy consists of seven levels (Fig. 5.6). Two levels refer to products and five levels determine the waste management procedures.

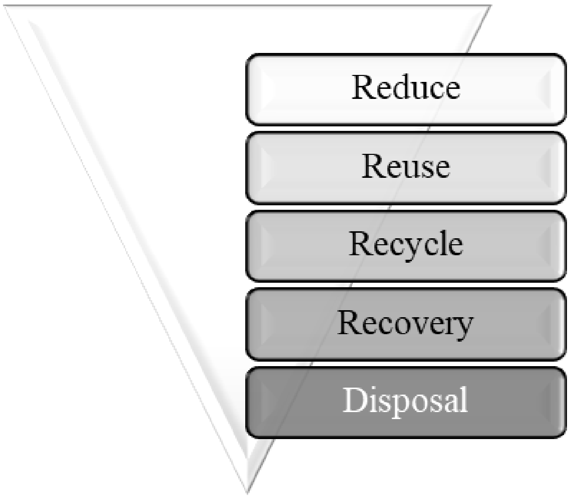

Fig. 5.5. Waste management hierarchy [6]
Rys. 5.5. Hierarchia postępowania z odpadami [6]

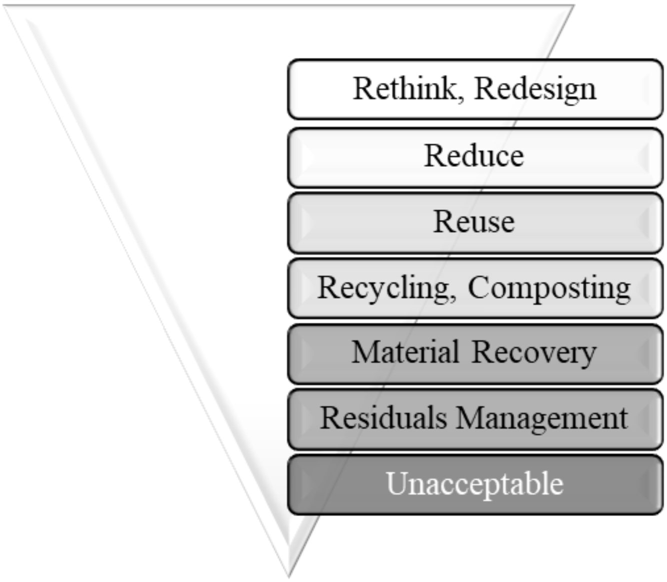

Fig. 5.6. Zero waste hierarchy [8]
Rys. 5.6. Hierarchia postępowania z odpadami dążąca do Zero Waste [8]

Level 3 refers to wastes and reflects Level 2 of the waste management hierarchy binding in the EU – preparation for the reuse. Preparation for the reuse requires such processes as cleaning, repair and renewal. The 4th Level of the hierarchy refers to the widely understood organic recycling. This level reflects Level 3 of the waste management hierarchy valid in the EU [6, 7]. The goal of the action is to transform selectively collected waste into precious secondary raw materials. An example of the above is the transformation of the collectively selected paper/cardboard into cellulose for the production of new packaging or the transformation of selectively collected biodegradable waste into manure which improves the quality of the soil. Another level of the Zero Waste hierarchy is material and chemical recovery. It consists in maintaining materials and resources within the closed circulation. In the new Zero Waste, the solutions which reach for the resources or constitute a nuisance to the environment are unacceptable [7, 8].

5.1.2. Waste processing methods

Thanks to the development of municipal waste management technology, it is possible to transform the waste into the source of the new raw material. Simplifying, we may divide municipal waste recovery technology into the recovery of materials and the recovery of energy. Recovery of the material may be achieved through mechanical, chemical and organic recycling processes. Recovery of energy may be realised through the thermal transformation of wastes to recover energy in the form of heat, steam or electrical power.

Recycling is a process which aims at the recovery of secondary materials and processing them to obtain new resources for the original or different use. The idea of recycling covers also the processing of biodegradable fractions. For many reasons, recycling as a transformation method of municipal waste is not always ecologically and economically justified. That is why the recovery of energy should be realised as a valuable method that allows us to take advantage of the potential of waste. The discussed method is an alternative to depositing waste at landfills. Municipal waste may be directly incinerated in the incineration plant or co-incinerated as a fuel component in cement plants or the professional power industry, for example, in heating plants or power plants [9]. The energetic use of municipal waste in the co-incineration process in furnaces for the clinker burning process is one of the directions of energy recovery. Furthermore, this solution results in saving natural resources and improves the quality of the environment by, for example, decreasing the wastes deposited in landfills. Depositing is the least advantageous and efficient process of neutralisation of municipal waste. Sustainable actions guarantee effective and reliable limitations of municipal waste depositing. It needs to be emphasised that the introduction of the bans will not solve the real problems. What is needed is a wide scope of actions from the increase of the responsibility of manufacturers who introduce products into the market to the changes in the consumers' habits. It is also necessary to introduce corrections to legal and economic regulations, for example, environmental benefits or certificates for recycled materials [9]. A holistic approach to the problem will make it possible to introduce equal changes to the market and create a demand for secondary products which come from the stream of municipal waste.

Analysing the Global Waste Index 2022 report, it may be observed that waste management differs between countries [10]. Many countries reach a high recycling level. The countries with the highest recycling level are Sweden, South Korea and Germany. Germany is considered a world recycling leader (Fig. 5.7).

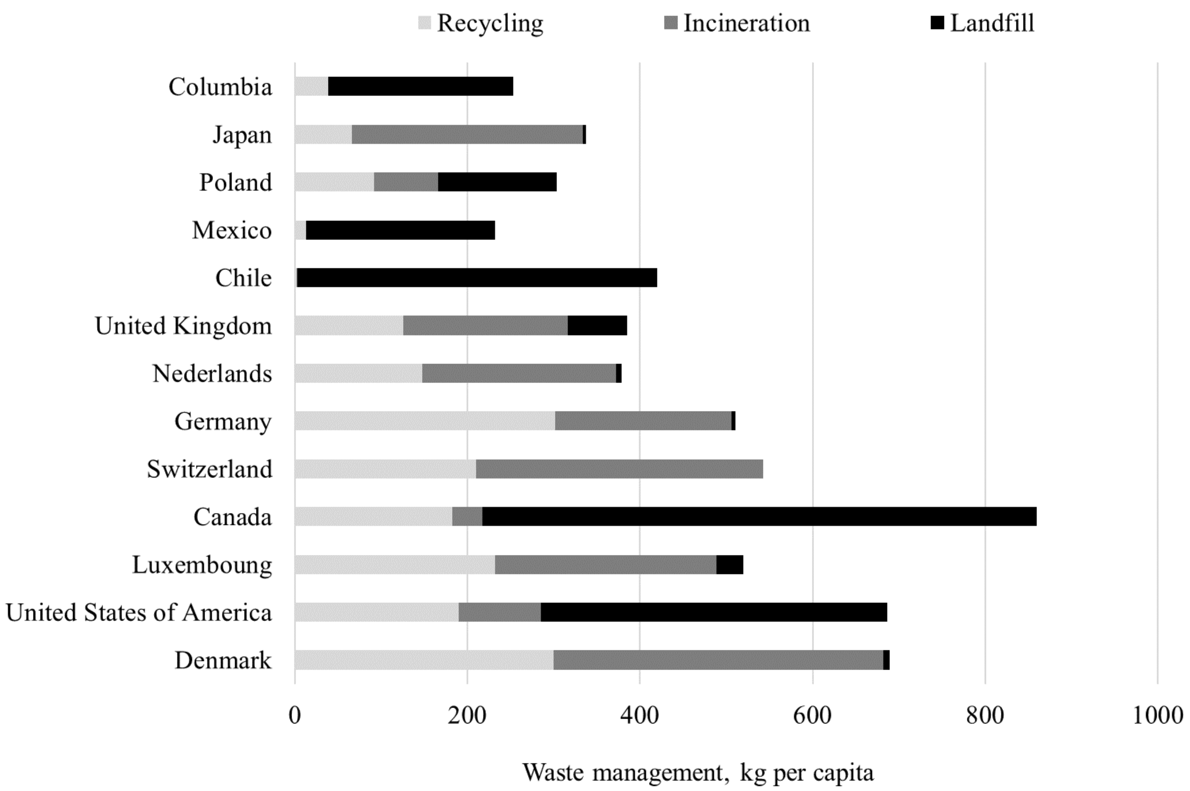

Fig. 5.7. Municipal waste management in selected countries [10]
Rys. 5.7. Zagospodarowanie odpadów komunalnych w wybranych krajach [10]

Out of the general amount of produced municipal waste in the European Union in 2020, 30% was directed for material recycling, 26% was incinerated, 24% was deposited in the landfill and 18% underwent compositing (Fig. 5.8). Waste management practices vary from country to country. In some EU countries, depositing in landfills is still a basic municipal waste management method. In such countries as Estonia, Luxemburg, France, Ireland, Slovenia, Italy, Lithuania and Poland about 1/3 of the generated municipal waste is deposited, while 40% is recycled and incinerated (except for Estonia) [4].

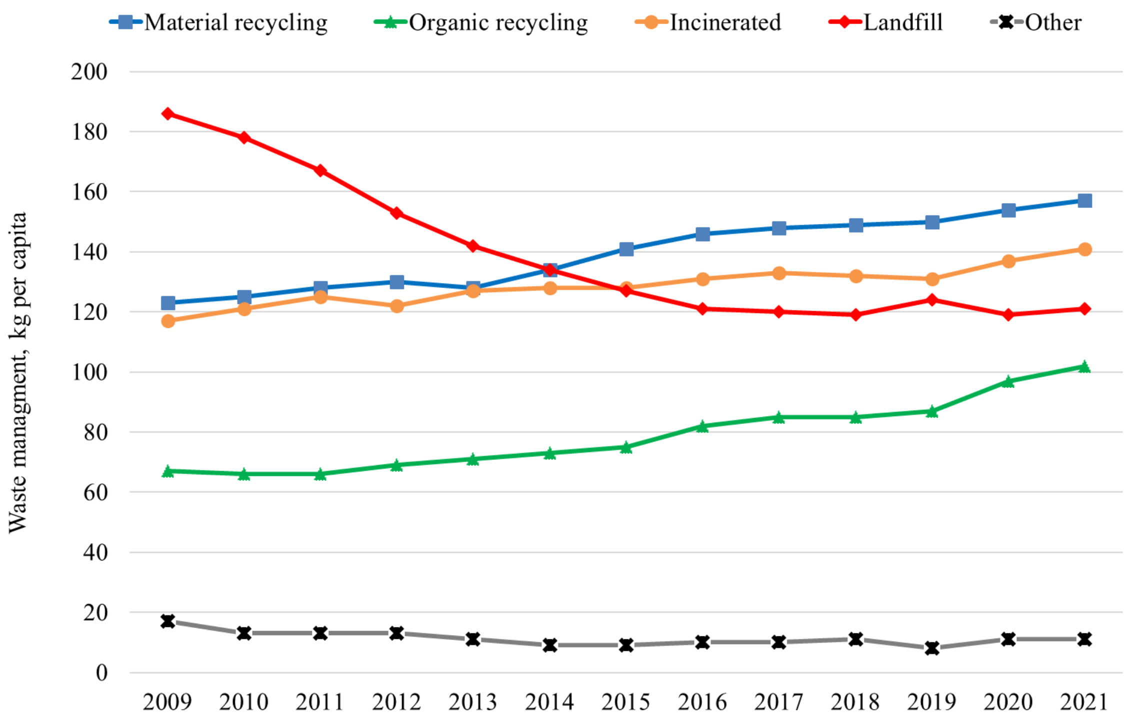

Fig. 5.8. Municipal waste by waste management operations in the UE, 2009–2021 [4]
Rys. 5.8. Zagospodarowanie odpadów komunalnych w UE w latach 2009–2021 [4]

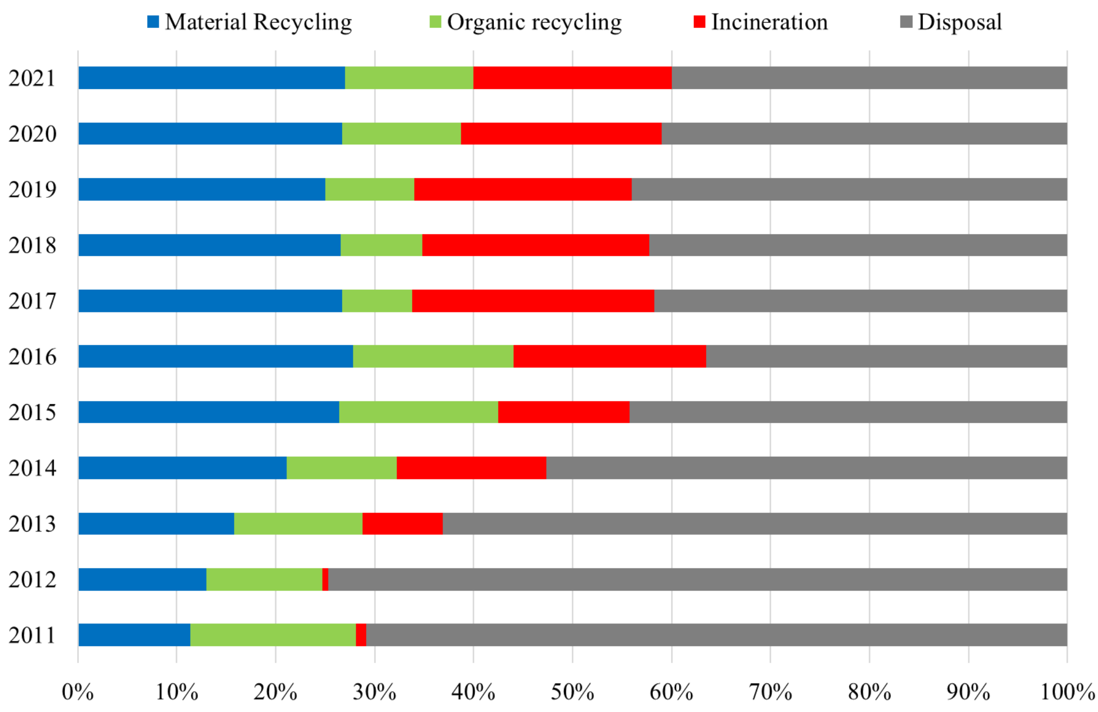

Fig. 5.9. Municipal waste by waste management operations in Poland, 2012–2021 [5]
Rys. 5.9. Zagospodarowanie odpadów komunalnych w Polsce w latach 2021–2021 [5]

In 2021 in Poland, out of all the collected municipal waste, 8.2 million tonnes was directed for recovery and it formed 60% of the produced municipal waste. 3.7 million tonnes (27%) was directed for recycling and 1.8 million tonnes, i.e. 13% was directed for composting or fermentation (Fig. 5.9). Thermal processing with energy recovery covers 20% (2,7 million tonnes) and 0.2 million tonnes (about 1% of the municipal waste for neutralisation by incineration without energy recovery [5]. It needs to be added that the energy recovery was realised through incineration and co-incineration processes. The remaining 5.3 million tonnes of municipal waste, which constituted 39% was deposited in the landfills.

5.1.3. Circular Economy

Circular Economy (CE) takes a new, pro-ecological and more sustainable approach than the linear economy. The linear economy operates on the grounds of the simple idea: produce → use → dispose of (Fig. 5.10) [11]. The discussed economic model has been functioning since the industrial revolution. In the linear economy, natural raw material is exploited and processed into a product. The product goes to the consumer, who uses it for a determined time. Once, the useful properties are lost, the product turns into waste terminating its life in the landfill.

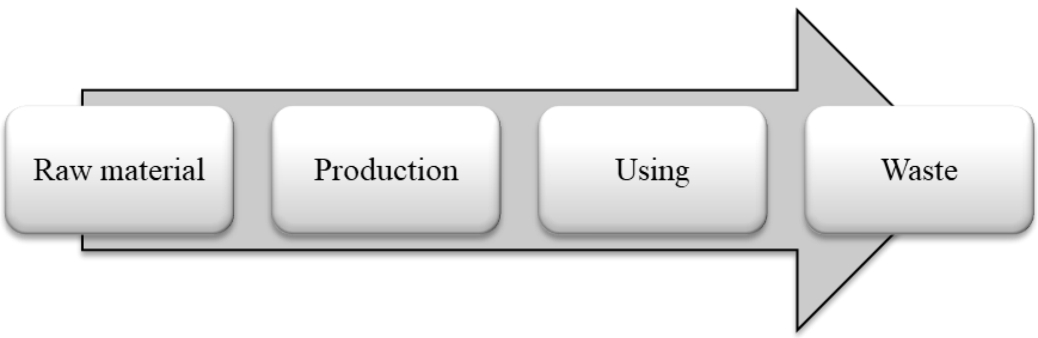

Fig. 5.10. Linear economy [11]
Rys. 5.10. Model gospodarki linearnej [11]

The main defect of the linear economy is the growing demand for raw materials. The linear economy model assumes that there will never be a shortage of resources and there will always be a place for depositing the waste. Continuation of such a model will shortly lead to the significant impoverishment or even total depletion of natural resources [11, 12]. With time, the resources started to shrink, their prices started to increase and the supplies became unstable. Once the problem was discerned, the remedy was introduced to the linear model in the form of recycling (Fig. 5.11). This solution enables the partial transformation of waste into material that can be reused in the production process. Currently, recycling is insufficient to stop the contamination of the environment. Moreover, during the recycling process, energy and water are also consumed.

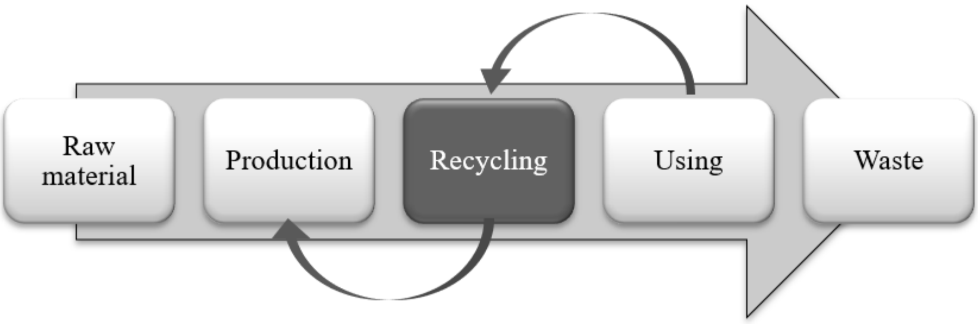

Fig. 5.11. Linear economy with elements of recycling [12]
Rys. 5.11. Model gospodarki linearnej z elementami recyklingu [12]

In order to achieve climatic neutrality, it is necessary to build an economy and society with zero emissions. Ecological transformation is possible when the circular economy is implemented. The circular economy is a concept according to which the use of primary resources and energy as well as the amount of waste is minimised by closing them in the loop of processes – use – reuse (Fig. 5.12) [13, 14].

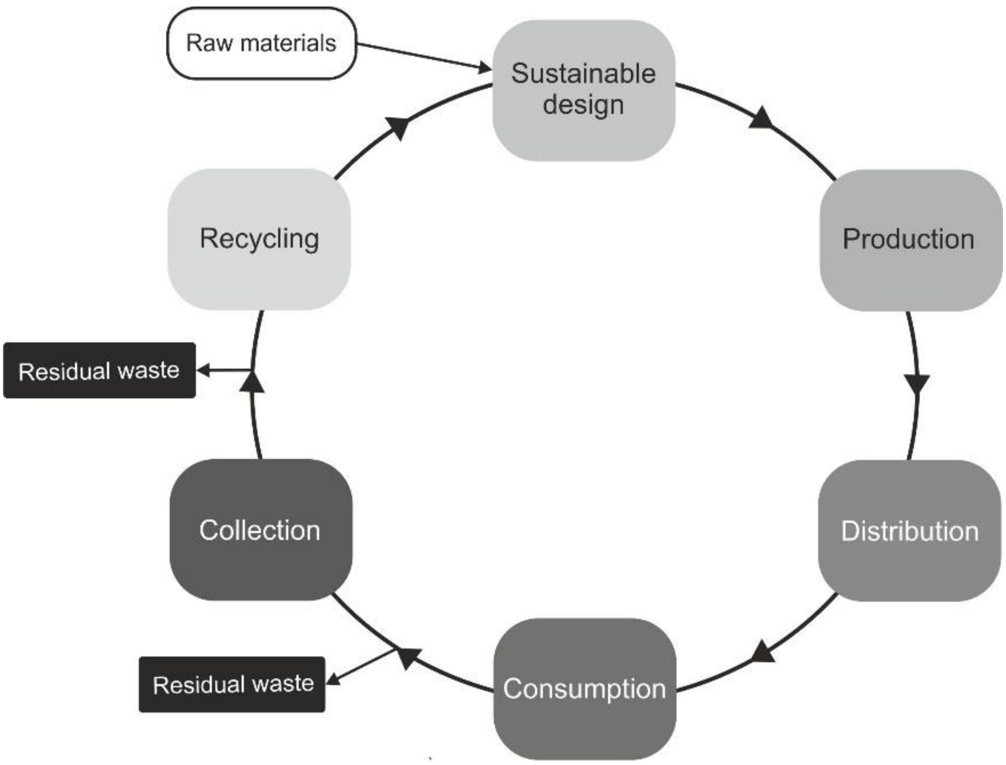

Fig. 5.12. Circular Economy (CE) [12, 13]
Rys. 5.12. Model gospodarki o obiegu zamkniętym (GOZ) [12, 13]

Implementation of the circular economy model requires the engagement and cooperation of many parties. It is necessary to have the support of lawmakers, non-governmental organisations and in particular manufacturers and consumers (Fig. 5.13). Joint engagement will bring many advantages to the protection of raw materials/resources, but also environmental, social and economic benefits.

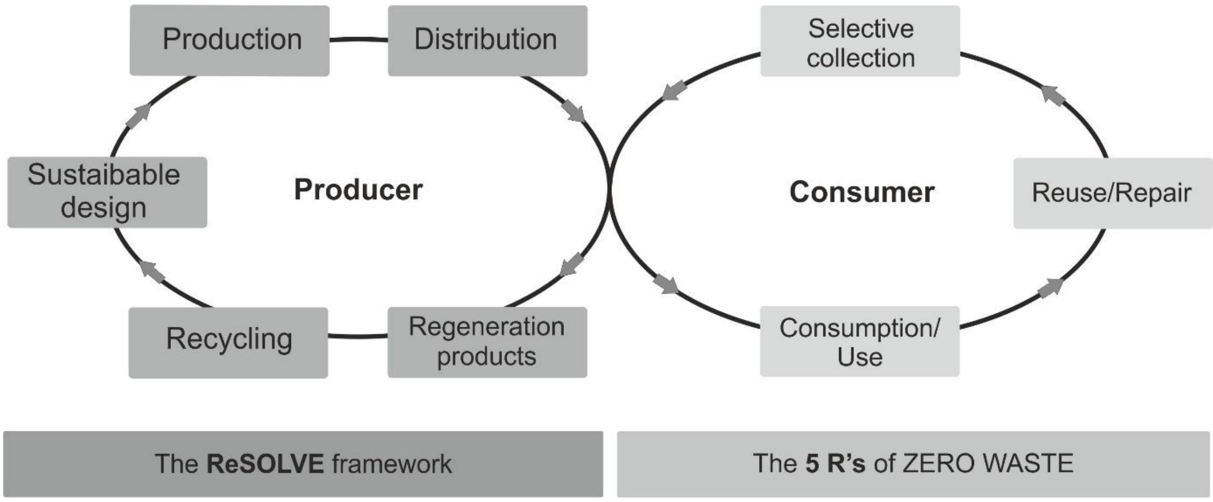

Fig. 5.13. Producers and consumers in the Circular Economy [15]
Rys. 5.13. Producenci i konsumenci w gospodarce o obiegu zamkniętym [15]

5.2. Responsible Consumer

Consumerism became a serious problem in the modern world. The obsessive need to possess dominates many aspects of the world economy. As a global society, we consume more and more. Excessive consumption corresponds to excessive production, and both result in a growing amount of waste and degradation of the natural environment. Further cultivation of the consumptive lifestyle brings us closer to the climatic catastrophe and depletion of resources for future generations. A key to achieving climatic neutrality is redefying social awareness. Proper ecological knowledge will help change the habits and create an appropriate consumer attitude. Conscious consumption means making proper choices based on knowledge about the social, ecological, economic and political consequences. Conscious consumption aims to divert social behaviours in the direction of more responsible and ecological consumer patterns. Every year we observe growing economic awareness of consumers [1, 15]. Nowadays, many consumers pay attention to selected features of products, such as their origin, production methods, materials used, not testing on animals, possibility to recycle or business practices of the producer. There is still a lot to do, but one may say that consumers are becoming more reasonable when taking their purchase decisions.

5.2.1. Zero Waste Philosophy

Zero Waste (No Waste) is an idea which aims at protecting all natural resources by responsible production, consumption, reuse and recovery of all products, packaging and materials. Zero Waste idea consists in gradual but complete elimination of waste. According to this philosophy, the waste is not incinerated or deposited because, on the one hand, it may be harmful to the environment and endanger the health of people and, on the other hand, deplete the valuable resources. Zero Waste is often defined as a minimalistic lifestyle. However, it is not a new approach. The Zero Waste idea was introduced in the 70s by an American chemist Paul Palmer. His concept was based on the reasonable use of resources without wasting them. The main assumption was designing products in such a way as to be able to reuse them many times, with no need to throw them away or recycle them [16, 17].

Nowadays, it is recommended to apply the 5R rule when thinking about following the Zero Waste philosophy. The 5R rule became popular after the publishing of the book by Bea Johnson: Zero Waste Home. The 5R consists of the following steps [18]:

- Refuse – the first principle assumes the reduction and limiting of the stream of the produced waste by refusing unnecessary things. This requires that the consumers take firm decisions. This is the art of saying no to products which are manufactured in a way that is detrimental to the environment. An example of such products are leaflets, business cards, advertising gadgets, drink straws or disposable products. These products have a short lifespan.
- Reduce – the principle refers to the decrease of the amount of waste by reducing the consumption of products. The principle motivates the consumer to minimise the purchase. It encourages to buy the necessary, indispensable things. This requires a well-thought approach to the purchase. It also prevents wasting food and products and results in a decrease in the stream of produced waste and implies some economic savings.
- Reuse – the third principle consists in reusing products. The idea of "reusing" comprises many possibilities: repair, transformation or finding new ways of application. The product may also be resold or given away for free. Examples are vases or candle holders made of jars or bottles, garden furniture of euro pallets,

flower pots made of used car tires and shopping bags made of advertisement banners. An old cotton t-shirt may be transformed into kitchen wipes. Damaged clothes may be repaired by a tailor and shoes by a shoemaker.

- Recycle – the principle reminds us that careful and reliable segregation of waste "at the source" increases the chances for its reuse. Not always can we find ways to use the waste on our own, that is why we need to direct the waste to special facilities. Such actions are a perfect example of Zero Waste.
- Rot – this reminds us about the possibility to compost biodegradable waste on our own. Biowaste rests from kitchens or gardens constitute a valuable material for fertilising soil in house gardens or flower pots. If it is impossible to make our compositing, the biowaste should be carefully segregated and disposed of in a brown waste container.

5.2.2. Less waste

Zero Waste is often defined as a minimalistic lifestyle. Such an attitude is not suitable for everyone, as it requires a strong change of habits and abandoning many necessities which causes radical changes to the actual lifestyle. For an average consumer, a Zero Waste idea is out of reach. Less demanding is a Less Waste style. Living according to the Less Waste idea means caring responsibly for the natural environment without drastic changes to habits [15, 16]. It may be said that turning to the Less Waste style will not require much effort or time from the consumer. It needs to be underlined that the Less Waste idea does not mean only a reduction of the stream of the produced waste, it also requires limiting the consumption. An important element of the Less Waste idea is the minimisation of the waste of food. Living according to the Less Waste lifestyle implies not only pro-ecological habits but also significant savings to the household budget [17, 18, 19]. Table 5.1 presents a few guidelines on how to live in a Less Waste style.

Table 5.1

Examples of a lifestyle according to the idea of Less Waste

In everyday life	• Replace drinks in plastic bottles with refillable bidons or bottles with filters, • Resign from credit card print-outs • Resign from single-use packaging for fruits and vegetables, • Go to work and the city centre by bicycle • Use public transport instead of your car

Table 5.1 cont.

In the kitchen	• Carefully plan shopping to avoid wasting food, • Give up on paper towels, • Replace foils with closed multi-use containers, • Use packaging which extends the durability of food
In the bathroom	• Use bio-cotton towers • Use ecological hygienic products or refillable products, for example, bamboo toothbrushes
In the closet	• Quality of clothes over quantity, • Clothes made of natural textiles should be the base, • Clothes should be of a timeless style, easy to match and crate many outfits
When travelling	• Replace traditional paper tickets with electronic tickets, • Resign from buying unnecessary souvenirs which collect dust and end up in a garbage bin • Use hygienic products (soaps, shampoo or conditioners) in bars which take less space and do not generate plastic waste.

Living according to the Zero Waste idea is difficult but it is possible and easy to introduce pro-ecological habits to everyday life. It needs to be stressed that both sustainable shopping and limited consumption are key to climate neutrality in the world.

5.2.3. Environmental education

In the face of the challenges, global climatic crisis and degradation of the natural environment, ecological education should be a priority for the present generations. It may be said that environmental education is a global challenge. Ecological education helps build a society on the grounds of sustainable development. Reliable knowledge increases the awareness of the relations between the environment, society and economy. Education in the field of sustainable development aims at creating conscious citizens who will be able to take responsible decisions in their private and collective life. In the world forums, it is underlined that new and future generations need to be equipped with the responsibility and ability to think critically and thoroughly [20]. Ecological education is a concept of forming and upbringing a society that acts according to the idea: “Think globally – act locally”. It needs to be underlined that ecological education is a priority for the world, Europe and Poland [20, 21].

According to the Europeans, climate change is one of the most serious world problems. The data show that 84% of young Europeans worry about climate change.

European Commission tries to increase the ecological awareness of the society through many initiatives, for example, “Coalition for Climate Educations” or “Scientists in School”. A complete list of initiatives for ecological education is available on the official website of the European Union [22].

In Poland, ecological education is realised formally and non-formally. Formal education is realised in educational institutions. Nowadays, in Polish educational institutions, ecology is incorporated into school programs within the framework of various subjects such as chemistry, technology, biology or geography. Students learn about issues related to environmental protection, climate changes, saving of energy, water, natural resources, segregation and use of waste. Implemented actions allow the shaping of pro-ecological attitudes [21, 23]. Another keystone is non-formal education. It embraces courses, scout groups or classes led by non-governmental organisations on sustainable development, and global and social education. Global education focuses on teaching about global relations which are increasingly important in the changing and globalised world. Another keystone of non-formal education is citizenship education. Its basic purpose is to impose knowledge on the citizens about how the country functions, and what are the binding laws, rules and social standards. An example of citizenship education are scout organisations [23, 24]. Other examples of pro-ecological actions are photographic contests, and events, such as cleaning the world, segregation of wastes, etc.

A thorough ecological education will allow for shaping a conscious and responsible consumer. Conscious and responsible consumption is a step towards the reduction of the amount of waste and a decrease in the use of natural resources [22, 23]. To achieve this, ecological education should be inscribed into the DNA of present and future generations throughout the world.

5.3. Sustainable production

In literature, there are many different definitions of a circular economy (CE). Liu [25] defines CE as “an economic system that is based on sustainable development and is less dependent on depleting natural resources compared to traditional economies, through the mechanism of waste recycling, which is reintroduced into the system”. From an economic perspective, CE is “an economy based on a spiral loop system that minimizes the flow of materials, energy, and environmental degradation, without limiting economic growth, technological progress, and social progress” [26]. The Ellen

MacArthur Foundation report states that “CE is an industrial system designed to be renewable and self-regenerative" [27]. In a CE, products are designed to be easily reusable, disassembled, and reassembled – or recycled – assuming that the key to economic growth is the reuse of large amounts of materials recovered at the end of the product life cycle, rather than sourcing new resources” [26]. This concept itself is another stage of the waste management approach, which has progressed from a linear economy through recycling and now to a target model.

The core idea of a circular economy is optimising the use of resources according to the 5R principle, and this concept places CE within the sub-discipline of industrial ecology [28]. Currently, due to environmental protection initiatives being developed and increasingly implemented in many countries such as China, Japan, the United States, and European Union countries, the CE concept is becoming a key direction for mainstream structural changes [29].

Entrepreneurs should be aware of these changes and adapt their operations to meet the new requirements of a circular economy. Support and proper information about new regulations are crucial to businesses, especially to smaller ones that may encounter greater difficulties in adjusting to the new requirements.

For example, by examining the increasing production of plastics since the 1950s and the growing use of plastic products, it can be seen how much they have contributed to the increase in plastic waste. This trend increases the risk of improper management of these wastes and has a negative impact on the environment. It should be noted that compared to other types of waste, plastic recycling remains at a low level. Currently, in the European Union, just over one-third of plastic waste is recycled, and some of it is exported beyond the EU borders and processed in third-world countries where different environmental standards often apply. That is why it is crucial to close the loops in companies and for producers to take responsibility for the wastes, not only plastics but all of them, especially at the production stage [30].

5.3.1. Circular business models

Business models in a circular economy focus on utilising resources efficiently, minimising waste, while generating value for both customers and businesses. In a circular economy, objects are designed and manufactured with the intention of being easy to repair, reuse and recycle.

The business model of a circular economy is an approach to the design, production and distribution of products that prioritises waste minimization, efficient and sustainable resource utilisation, and the optimisation of production processes [31].

In this model, companies strive to reduce the consumption of natural resources by utilising the existing materials and products in subsequent stages of production. It aims to decrease the amount of waste by reintroducing it into the production process instead of sending it to landfills or incineration.

A circular economy and its business models are based on three fundamental principles [32]:

- Waste minimisation: This model prioritises minimising the amount of generated waste by avoiding material and energy losses at each stage of the production process. Waste that is generated becomes a resource for producing new products.
- Efficient and sustainable resource utilisation: This model emphasises the sustainable, efficient and safe utilisation of natural resources, ensuring a balance between social, economic and environmental needs. Designing processes and waste management considering the full life cycle is taken into account.
- Optimisation of production processes: This model assumes that production processes should be organised in an efficient manner to minimise the losses and waste. Optimising processes requires innovative technological solutions as well as changes in organisation and production management.

5.3.2. Business model divisions in the circular economy

The circular business model aims to achieve sustainable economic development, minimise negative environmental impact, and create a more efficient and resilient economic system. It is a response to the growing issues related to resource depletion, environmental pollution and climate change. An example of categorising business models is the widely recognised circular model, which identifies seven models that can be considered approaches to a circular economy within a specific enterprise [33]. This classification is presented in Figure 5.14.

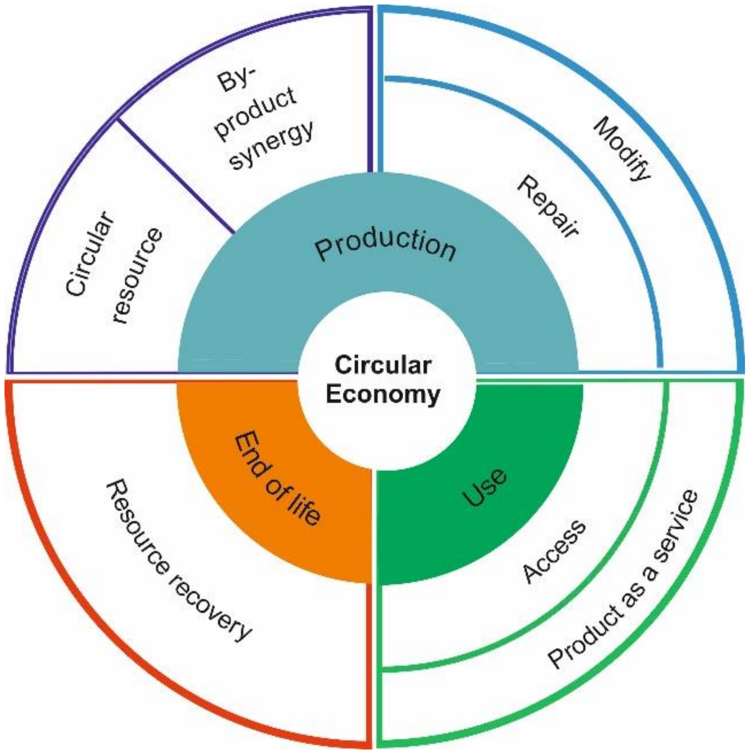

Fig. 5.14. Circular economy business models based on a circular model [33]
Rys. 5.14. Modele biznesowe gospodarki o obiegu zamkniętym na podstawie modelu kołowego [33]

The circular model includes seven business models, depending on the three stages of the entrepreneurs' lifecycle – Production, Use, End of life [33, 34]:

- 1 – Circular Resource: This model focuses on ensuring that resources and products used in production are constantly circulated and utilised for as long as possible – they are circular or at least recyclable or reusable. Examples include products with material passports or well-known product carbon footprints that can be compared in order to choose the most environmentally friendly option.
- 2 – By-Product Synergy: In this model, companies identify and utilise by-products or waste generated in their production processes as resources for other industries or businesses, including their own. This helps avoid waste and promotes closed-loop material cycles.
- 3 – Modify: This business model involves processing and modifying waste or products to extend their lifespan, increase durability, or add additional functions that can be utilised in the future.
- 4 – Repair: This model focuses on repairing damaged products instead of replacing them with new ones. Companies offer repair services and provide spare parts to prolong the life of products and reduce waste.
- 5 – Product as a Service: This model assumes that the company remains the owner of the product, and customers pay for its use as a service rather than owning it. The

company has an incentive to provide durable, easily repairable and recoverable products, since it is responsible for their maintenance and end-of-life management.

- 6 – Access: This model involves enabling customers to access products when they need them instead of owning them. An example is a bike-sharing service, where users can use bicycles for a specific period. This approach reduces the production of new products and the consumption of resources for their production.
- 7 – Resource Recovery: This business model focuses on recovering resources from waste that can be reused in production processes. Companies specialising in resource recovery collect, sort and process various types of waste to retrieve valuable materials. Examples include plastic recycling, glass recycling, paper recycling, as well as energy recovery from high-calorific waste.

Another division of business models is the RESOLVE framework created by the Ellen MacArthur Foundation, which is also one of the first and best-known frameworks. It consists of six business concepts, represented by the acronym RESOLVE, as presented in Fig. 5.15 [35].

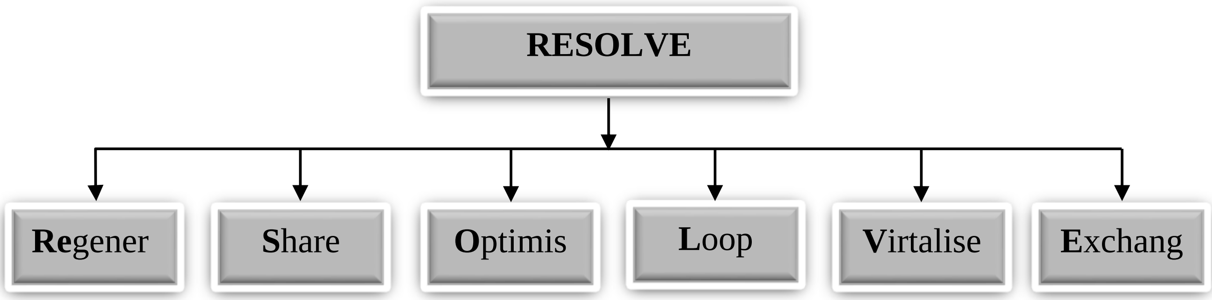

Fig. 5.15. The concept of models in the circular economy Resolve [35]
Rys. 5.15. Koncepcja modeli w gospodarce o obiegu zamkniętym Resolve [35]

Resolve model can be divided into [34, 35]:

- Regenerate: The regenerative business model involves recovering, repairing and processing used products, materials or resources to create new products or extend the lifecycle of the existing ones.
- Share: The sharing business model assumes that resources are shared and used by multiple individuals or organisations. Instead of buying products, customers can rent or share them, contributing to the efficient use of resources.
- Optimise: The optimisation-based business model focuses on optimising production processes and resource utilisation to minimise waste and increase efficiency. This is achieved through the use of new technologies, automation, process improvement and proper waste management.

- Loop: The looping business model assumes that products and resources are designed to be easily recycled and reintroduced into the economy. This is accomplished through strategies such as designing products for disassembly and material reuse.
- Virtualise: The virtualisation business model involves moving traditional products and services into the virtual online space. This also applies to physical memory media, as content is provided in a digital form in the cloud instead of using them (e.g. CDs or DVDs).
- Exchange: The exchange-based business model focuses on creating platforms where users can exchange products, services or resources with each other. Such platforms can facilitate direct exchange between users or act as intermediaries, enabling transactions between parties, ultimately leading to the reuse of products without them ending up in landfills..

This division, similar to the circular model, focuses on various solutions for maximising the use of waste as materials for new products, as well as minimising losses and maximising utilisation during the usage phase.

Different approaches to the concept of a circular economy can also be distinguished, with the most comprehensive being the 7R model presented in Figure 5.16 [33].

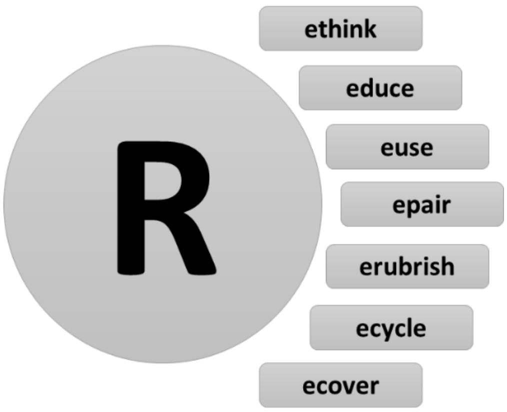

Fig. 5.16. Model 7R [33]
Rys. 5.16. Podejście 7R [33]

The 7R approach describes various forms of product or waste utilisation within a company. All of them revolve around a new waste management hierarchy, starting from designing with the full product life cycle in mind (Rethink), followed by waste reduction (Reduce) and opportunities for reuse (Reuse), then repair (Repair) and refurbishment (Refurbish), and finally recycling (Recycle) and recovery (Recover). This concept assumes that no waste will be left unused. It expands upon the 5R concept presented in Chapter 5.2.1., but with a stronger focus on waste management in specific projects and companies.

The development of each "R" can be understood as follows:

- Rethink refers to the need to reconsider our habits and behaviours, especially in the context of consumption and exploitation of natural resources. It involves reflecting on how we act and make decisions to reduce our impact on the environment.
- Reduce emphasises the need to decrease the amount of resources consumed and waste generated. It involves limiting production and consumption in favour of a more sustainable lifestyle. Striving to minimise energy, water, material and other resource consumption is crucial for reducing our ecological footprint.
- Reuse entails seeking to reuse items and materials as much as possible instead of discarding them. By repairing, refurbishing, transforming or passing on items to others, we can reduce waste and extend the product life cycle.
- Repair encourages repairing damaged items instead of replacing them with new ones. Repairing extends the lifespan of products and reduces the need for new production, which has a positive impact on the environment.
- Refurbish refers to the process of restoring items to a usable or aesthetically pleasing condition through cleaning, painting, refurbishment and other actions. Refurbishing allows us to extend the lifespan of items and to avoid wastage.
- Recycle involves processing waste to obtain new raw materials or products. By segregating and sending materials to appropriate recycling processes, we can reduce the amount of waste sent to landfills and the need for extracting new resources.
- Recover pertains to the processes of extracting value from waste that cannot be recycled. Organic waste can be processed into biogas or compost, and energy waste can be utilised for energy production. Through recovery, we can maximise the resource and energy potential of waste.

There are many other models and concepts related to the circular economy, such as those based on the BS 8001 standard, The Circular Economy Handbook, the model developed by the Amsterdam-based institute IMSA, or the Circle Economy organisation. However, all of them are based on principles associated with the fundamental concept of the 3R (Reuse, Reduce, Recycle), which assumes that there is no waste [33].

The implementation of a circular economy applies to all sectors and stakeholders, with waste performing a crucial role in the entire concept. The aim is to close the loops within businesses or establish economic symbiosis among enterprises. Of course, such a solution and comprehensive approach poses significant challenges, particularly when dealing with hazardous waste, such as ash from waste incineration or other combustion processes, as well as in the realm of chemicals or hazardous materials. However, striving in this direction is part of achieving sustainable development goals, not only in waste management but also in other areas.

5.3.3. Business model examples in companies

Examples of smaller businesses and their implemented business models in the circular economy are based on various models. Not all of them are directly related to waste management, but they all aim to reduce waste generation and either minimise or close the waste loop. Considering the circular model and the categorisation into the seven types of business models. Table 5.2 presents examples of companies that have implemented these models in their enterprises.

Table 5.2

The examples of circular models in companies

No.	Model	Example	Source
1	Closed-Loop Resource	The company Loop collects used packaging from consumers and retail customers, allows for deposit returns if provided by the manufacturer, sorts and stores the collected packaging, and ultimately returns cleaned packaging to manufacturers for refill purposes.	https://exploreloop.com/
2	By-product synergy	Stora Enso – The production process at Stora Enso inevitably generates residues and waste such as dust, sawdust, black liquor and wastewater. These waste materials are utilised for internal purposes, such as bioenergy or pulp production, as well as supplied outside the company to its suppliers for agricultural or road construction use. Additionally, the mills used in the production require a significant amount of water. The company returns 96% of the water back into the circulation after prior purification.	https://www.storaenso.com/pl-pl/sustainability
3	Modify	Ecovative Design LLC is a company based in Green Island, New York, that provides sustainable alternatives to plastics and polystyrene foams for packaging, construction materials and other applications using mushrooms – an advanced technology for producing an innovative substitute.	https://www.ecovative.com/

Table 5.2 cont.

4	Repair	Patagonia company offers its customers services for repairing their products or returning them, and through an online platform, other customers can purchase used clothing at a lower price. This allows customers to extend the lifespan of garments, contributing to waste reduction.	https://eu.patagonia.com/pl/en/stories/our-quest-for-circularity/story-96496.html
5	Product as a Service	Philips company offers its customers LED lighting along with comprehensive service support. Customers do not have to invest in purchasing light bulbs, but instead receive a continuous and comprehensive lighting service.	https://www.lighting.philips.pl/usługi
6	Access	Traffic car company offers its customers the option to rent cars by the minute. Customers do not have to invest in owning their own car, and the company maximises the utility of the vehicles while earning income from rentals. Similar situations can be observed with bike-sharing and electric scooter rental systems, which are increasingly common throughout Europe. Airbnb enables its users to rent apartments and rooms from other platform users. This way, users do not have to rely on hotels and other traditional forms of accommodation, which makes use of the existing infrastructure.	https://traficar.pl/ and Airbnb.com
7	Resource Recovery	TerraCycle specialises in recycling hard-to-process waste, such as chip bags or paper cups from beverages. The processed materials are used to manufacture new products.	https://www.terracycle.com/en-US/

There are many examples of companies implementing business models related to the circular economy. However, most companies focus on implementing actions within a narrow scope of their operations. These actions may include waste management in production, changing habits and behaviours among employees, implementing solutions for water, energy and material savings, incentivising recycling in various ways, or utilising materials for other branches within the company. Even these actions form the basis for discussing circular business models and emphasising the importance of the right approach to this topic.

Global companies also strive for recognition in the field of the circular economy. Examples of such well-known companies may include:

- RePack is an innovative solution introduced by a Dutch company aimed at promoting the circular economy in the online shopping sector worldwide. It involves renting and returning special packaging in which products are delivered from online stores. This allows the packaging to be reused multiple times, reducing waste and minimising the negative impact on the environment.
- IKEA has introduced a service called “Buy Back and Give Back” targeting customers to promote the circular economy. As part of this service, customers can bring in used IKEA furniture that is less than five years old and listed in the selected products catalogue. The furniture can be sold at the Customer Service Department. Prior to visiting the store, customers need to visit a dedicated IKEA webpage to get a valuation for their furniture. Upon accepting the valuation, customers can bring the furniture to the store, where it is checked against the previously offered quote. In exchange for the furniture, customers receive a refund card that can be used for purchases at IKEA stores, both in-person and online. The used products, on the other hand, go to the “circular hub” department, where they can be purchased at an attractive price by other users.
- BASF’s recycling of car batteries is a solution that allows closing the loop in the electromobility industry. BASF is currently developing an innovative and highly efficient process that brings numerous benefits. This process enables the recovery of significant amounts of high-purity lithium while minimising waste generation and reducing the carbon footprint compared to the existing methods. As such, BASF supports the goals set by the European Commission to create a sustainable value chain for car batteries in Europe. The recycling process being developed by BASF can perform a significant role in building a circular economy for car batteries in Europe.
- Castorama, in collaboration with Deko Eko and Stena Recycling, has decided to utilise packaging film as a raw material for creating eco-friendly plant pots. The aim is to transform the film waste from protective packaging for pallets, cartons and individual products into gardening products. This innovative process allows the conversion of film waste into durable, functional and aesthetically pleasing plant pots. As a result, film waste is effectively utilised within a closed loop, contributing to waste reduction and minimising the negative environmental impact.

Although the Netherlands is considered a highly developed place of the circular economy, Poland can also boast good examples of environmentally conscious businesses in line with the principles of the circular economy. Some of these companies include:

- Aluprof – Aluprof is one of the largest producers of aluminium systems on the European market. The company focuses on implementing a circular economy model by recycling aluminium and minimising the consumption of natural resources. Aluprof also invests in renewable energy development and optimising the energy efficiency of its manufacturing processes. It is worth mentioning that aluminium has one of the highest recycling rates, primarily because it can be recycled an infinite number of times.
- Zakłady Azotowe Puławy – Zakłady Azotowe Puławy is one of the largest producers of fertilisers and chemicals in Poland. The company operates in the chemical sector but strives to implement the principles of a circular economy and focuses on development based on green hydrogen and the utilisation of waste streams from production processes. Green hydrogen entails hydrogen production based on renewable sources and reused or recycled products.
- Lafarge Polska – Lafarge Polska is a manufacturer of building materials, including cement and concrete. The company operates in accordance with the principles of a circular economy and takes actions aimed at the efficient utilisation of industrial waste, including ashes from power plants.

The ashes generated from combustion in power plants can be used as an additive in cement production. The ashes are thoroughly analysed and undergo a processing process that involves mixing them with other components, such as cement clinker, to achieve the optimal composition and properties of the cement [36].

CEMEX is also an example of ash utilisation. The principles of a circular economy are implemented by CEMEX in three stages of the production process: in the selection of raw materials, the use of fuel and the management of waste generated in the production process, as well as waste heat. In 2021, CEMEX plants in Poland utilised nearly 900,000 tons (897,111 metric tons) of alternative raw materials, which had the status of waste or by-product. Among them, over 120,000 tons (121,359.48 metric tons) of ashes were used in concrete production. The average share of waste materials in the total balance of cement plants was approximately 22%. Such activities by CEMEX contribute to the creation of closed material loops between different industries, known as industrial symbiosis, and this is a good example of their operation. [37]

This last example demonstrates the efficient utilisation of difficult-to-manage waste, which helps reduce the amount of waste disposed in landfills and decrease the consumption of natural resources, such as clinker in cement production.

5.4. Summary

The topic of waste management and responsible consumption highlights the importance of changing our consumption habits and the impact we can have on waste reduction. The concepts of zero waste and less waste are the most popular trends when it comes to individual actions and grassroots consumer initiatives.

Education on waste management is also a crucial element. This topic emphasises the importance of increasing public awareness regarding waste issues, their environmental consequences and available solutions for dealing with them. Through education, consumers can better understand the impact of their consumption choices on waste generation and learn to make more responsible decisions. It is also important to emphasise consumer responsibility in waste segregation.

The implementation of the circular economy concept, as a new approach to waste management hierarchy, varies depending on different cultural, social and political systems worldwide. In China, the implementation of the circular economy is based on integrating closed material loops and industrial symbiosis, which are part of the country's global development strategy.

In the European Union and the United States, the circular economy concept primarily focuses on effective waste management. In these regions, particular attention is paid to practices associated with the circular economy, aiming to increase the responsibility of producers and consumers in the use of materials and products. The implementation of these practices is also observed in other parts of the world, such as Taiwan, Korea and Japan [29].

The main responsibilities of businesses related to the circular economy, especially in the waste management and extended producer responsibility areas, are defined by various regulations on national and European levels. However, it is important to understand that environmental protection regulations often undergo changes. For example, in the near future, there will be opportunities to assess the effectiveness of the current system and introduce changes or new solutions in accordance with new regulations.

The new requirements primarily include raising the levels of municipal waste recycling to 55% by 2025, 60% by 2030 and 65% by 2035. High targets also apply to packaging, where a recycling level of 65% should be achieved by 2025 and 70% by 2030 [2].

Particular attention should be paid to small and medium-sized enterprises within this system, as adapting to new regulatory requirements presents greater organisational and financial challenges compared to large enterprises. Therefore, gaining early knowledge about future changes in the law is valuable. Changes in the circular economy in Europe are most often initially introduced at the European Union level, for example, within the Taxonomy, European Green Deal or Fit55 program [38, 39, 40], and then incorporated into Polish law.

Despite the difficulties in implementing the circular economy and increasing the level of waste recycling, numerous examples of circular economy business models can be found, which is also crucial in the context of waste management itself undergoing significant changes. This occurs not only in terms of legal changes but also in approaches to waste and their importance within businesses. However, Europe, as well as the rest of the world, still faces many challenges to achieve complete circularity.

In the last decade, we have experienced the warmest period in recorded meteorological history. The average global temperature has risen by approximately 1°C compared to pre-industrial times, and in Europe, it has increased by almost 2°C. At the same time, we are observing an irregular distribution of rainfall over time and space, which is also more intense than before. As a result, we are increasingly facing extreme weather events. According to data from the European Environment Agency, between 2010 and 2020, Poland suffered financial losses exceeding 88 euros per capita due to these changes [41, 42].

Mitigating climate change and protecting the natural environment for future generations pose urgent challenges. Proper waste management and the implementation of circular economy principles are key actions to meet these challenges [43].

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6. AMBIENT AIR – POLLUTANTS, EMISSIONS, REGULATIONS, STATE OF QUALITY

The idea of sustainable development is based on the balance and sustainability of its three basic dimensions, i.e. economic, environmental and social. It creates the base for a long-term process aimed at improving the quality of life and meeting the needs of temporal and future generations. The economic dimension of sustainable development relates to economic growth and efforts to ensure access to all types of goods and services. The environmental dimension mainly refers to care for the environment, including the protection of natural resources, improving its condition and taking initiatives to reduce the consumption of natural resources. It is also important to keep in mind the social dimension relating primarily to efforts to improve the quality of human life.

A special role in these three aspects is played by the quality of ambient air, which is crucial to the health of people and ecosystems. Air pollution brings significant consequences both financially and economically. It causes harm in terms of the social cost of mortality and morbidity, as well as directly to the household budgets. The negative effects of air pollution are not limited to human health alone. Many other factors are worth considering: those relating to the human's closest part of environment (e.g., the condition of buildings, structures and infrastructure), and also natural aspects as the condition of animals, plants and larger ecological systems. Therefore, every effort should be made to improve air quality by reducing emissions in all possible areas.

6.1. Health risks of air pollution

The World Health Organization (WHO) has identified climate change as one of the greatest health threats of the 21st century, and air pollution as one of the greatest environmental threat to the public health and economic progress in the modern world [1]. The pollutants with the most serious impacts on human health are particulate matter, sulphur dioxide, nitrogen dioxide and ground-level ozone, as well as benzene, benzo[a]pyrene (B[a]P), dioxins and heavy metals. Their synergistic effect is particularly dangerous [2, 3]. They are the main cause of illness and premature deaths caused by cardiovascular diseases as well as respiratory diseases, predominantly lung diseases and lung cancers, nervous and endocrine systems diseases, fertility problems or acceleration of neurodegenerative processes [4–7]. The combined effects of ambient air pollution and household air pollution are associated with 6.7 million premature deaths annually and affect everyone in low-, middle- and high-income countries [1]. Although everyone is exposed to ambient air pollution, the higher disease burden attributable to household air pollution is mainly a result of very high exposures experienced by members of solid fuel-using households.

In 2016, the mortality rate above 140 per 100,000 population was spotted in Southeast Asia, Western Pacific regions and in most countries of low- and lower-middle-income countries, whereby the highest score has been noted in the Sub-Saharan Africa regions (Fig. 6.1). Here countries such as Sierra Leone, Nigeria, Chad, Côte D'ivoire, Niger, Togo, where the mortality rate is among the highest in the world and amounts to 324, 307, 280, 269, 252, 250 per 100,000 population, respectively (Fig. 6.2), should be highlighted. It is worth emphasising that the symptoms of diseases caused by air pollution are noticeable with a long delay after the exposure.

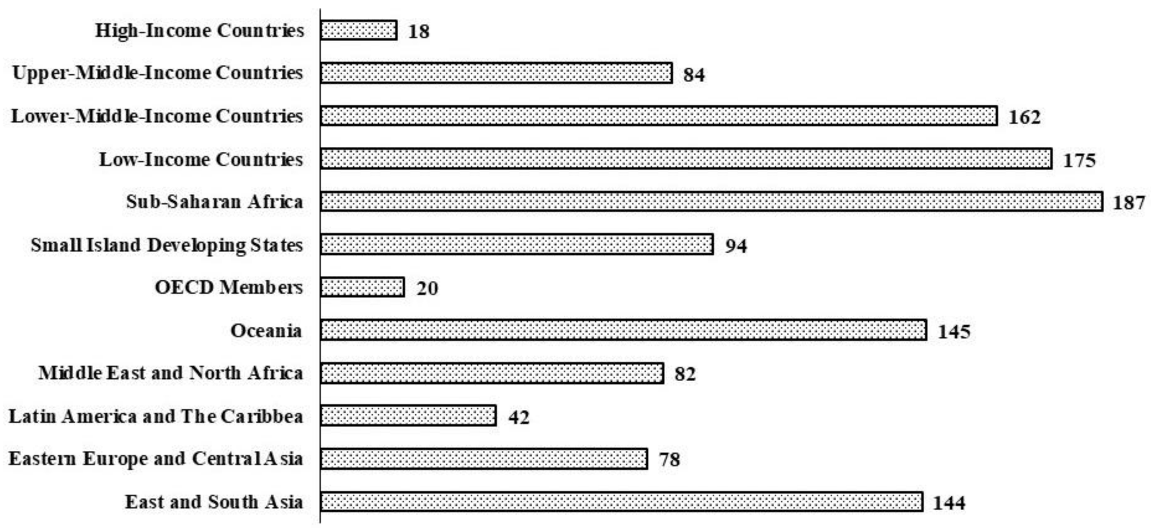

Fig. 6.1. Mortality rate from household air pollution and ambient air pollution by countries with varying degrees of wealth in 2016 (per 100,000 population), adapted from [8, 9]

Rys. 6.1. Współczynnik umieralności z powodu zanieczyszczenia powietrza w gospodarstwach domowych i powietrza atmosferycznego w krajach o różnym stopniu zamożności w 2016 r. (na 100 000 mieszkańców), na podstawie [8, 9]

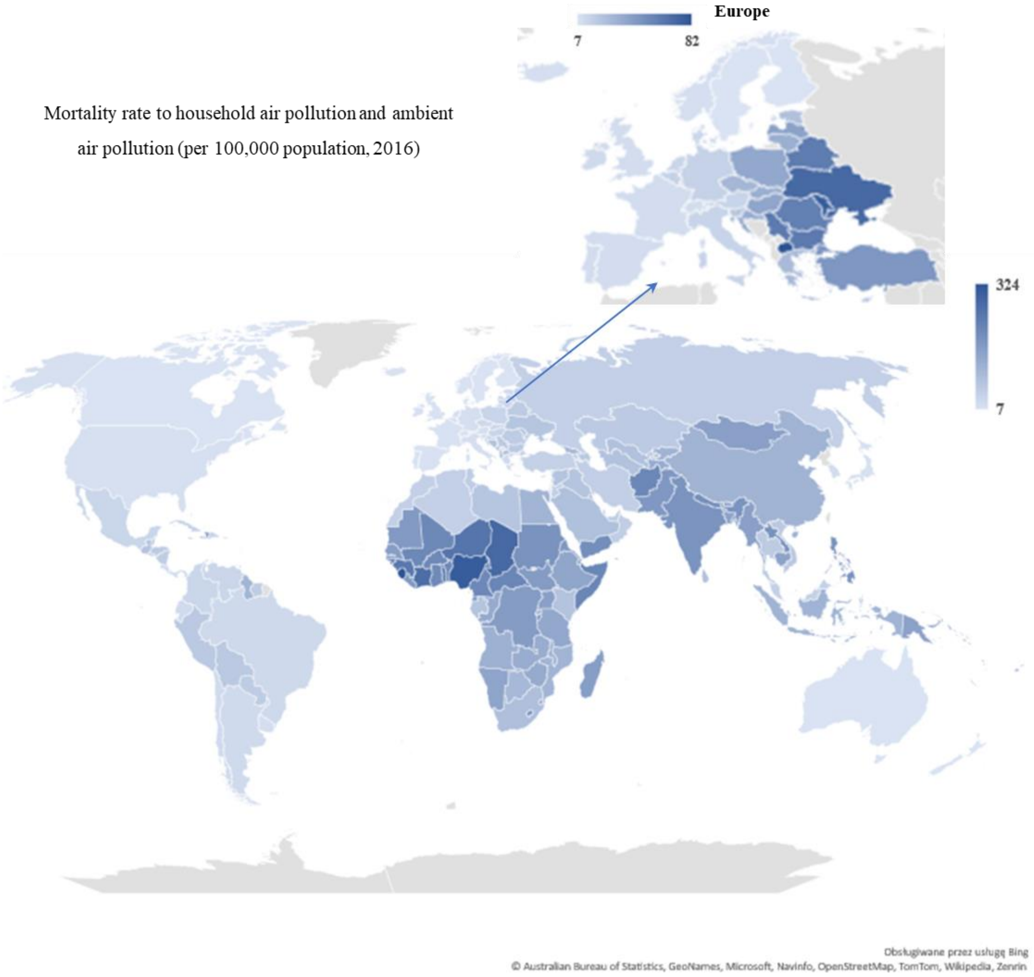

Fig. 6.2. Mortality rate to household air pollution and ambient air pollution by country in 2016 (per 100,000 population); adapted from [8, 9]

Rys. 6.2. Współczynnik umieralności z powodu zanieczyszczenia powietrza w gospodarstwach domowych i powietrza atmosferycznego w 2016 r. (na 100 000 mieszkańców) na podstawie [8, 9]

Air pollution is the second leading cause of deaths from noncommunicable diseases (NCDs) after tobacco smoking, according to WHO. As mentioned globally, household and ambient air pollution causes seven million premature deaths each year, including more than five million caused by NCDs related to air pollution [10]. Air pollution has, therefore, been identified as the fifth major risk factor in the latest political declaration of the United Nations General Assembly on the prevention and control of non-communicable diseases. In the WHO European Region, more than 550 000 deaths were attributable to the joint effects of household and ambient air pollution in 2016. Polluted air is responsible for 33% of new cases of childhood asthma, 17% of lung cancer, 12% of ischemic heart disease, 11% of heart attacks and 1% of chronic obstructive pulmonary disease in this region (Fig. 6.3). Therefore, the most important goal is to reduce the number of diseases and deaths caused by polluted air, as well as to protect the most vulnerable people, including pregnant women, children, the elderly and the chronically ill and people living in difficult socioeconomic conditions.

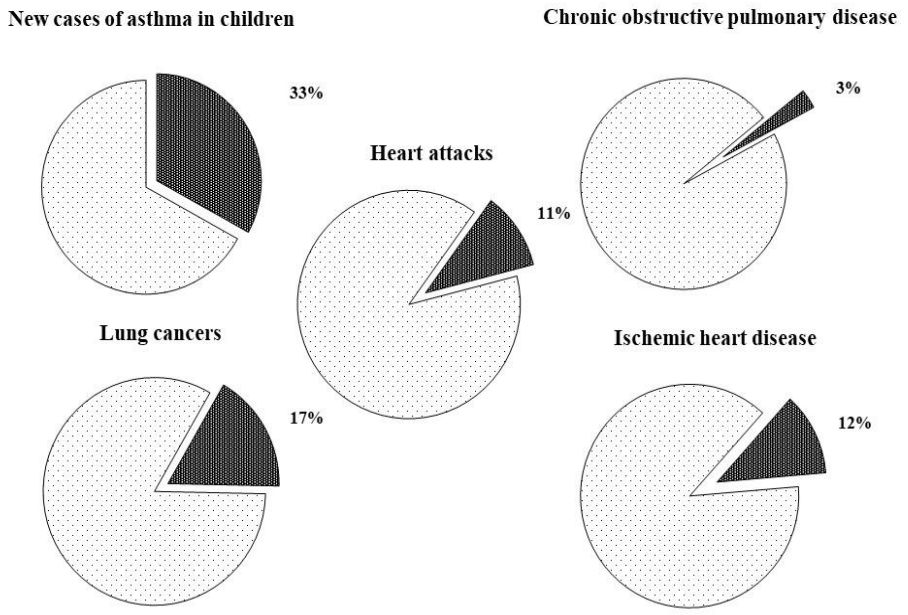

Fig. 6.3. Percentage of non-communicable diseases caused by air pollution in the WHO European Region [11]
Rys. 6.3. Odsetek chorób niezakaźnych spowodowanych zanieczyszczeniem powietrza w Europejskim Regionie WHO [11]

Research shows that the environmental burden of disease varies across Europe. In areas with significant environmental pollution, negative health effects are seen more often. According to the European Environment Agency (EEA) latest estimates, 307,000 people died prematurely due to exposure to PM2.5 in the EU in 2019. At least 58%, or 178,000, of these deaths could have been avoided if all Member States achieved the new WHO recommended air quality standard of 5 $\mu g/m^3$, for fine particulate matter (PM2.5).

The European Zero Pollution Action Plan (as part of the European Green Deal) sets a target of reducing premature deaths due to exposure to PM2.5 by more than 55% by 2030 compared to 2005. EU reports show the number of these deaths related to air pollution fell by about 30% between 2005 and 2019. We can take that the European Union is currently on track to achieve the assumed goal [12].

6.2. Human health effect of pollutants

6.2.1. Particulate matter

Among the atmospheric pollutants, a particulate matter with an aerodynamic diameter equal or less than 10 μm (PM10) has the most adverse effects on the human health [13, 14]. Dust particles PM1 (aerodynamic diameter ≤1 μm) and PM2.5 (aerodynamic diameter ≤2.5 μm) are especially dangerous as they have the ability to easily penetrate into the alveoli and then into the circulatory system [15, 16]. According to the World Health Organization (WHO), prolonged exposure to PM2.5 particulate results in an increase in the incidence of lower respiratory tract diseases, cardiovascular disease and increases the likelihood of lung cancer. Moreover, particulate matter is classified by the International Agency for Research on Cancer (IARC) as carcinogenic to humans (Group 1) [17]. Epidemiological studies have shown that there is an association between total mortality, cardiovascular mortality, respiratory mortality, hospital admissions and ambient PM10 level [18]. Apart from the described health consequences, the absorption of dust particles by living organisms constitutes a significant threat with regard to the various chemical compounds that are absorbed and usually have toxic, carcinogenic and mutagenic effects [15, 19–21]. In addition, some components of the dust particles can cause allergic reactions. Particularly dangerous are toxic metals and their compounds, persistent organic compounds, among them PAHs and sulfates and many others, adsorbed on fine dust particles. It is estimated that inhaling air containing fine particulate matter caused around 6.5 million premature deaths globally in 2019 [22].

There is strong evidence for a causal association between both short-term (hours/days) and long-term (months/years) exposure to ambient PM and a range of adverse health outcomes (mortality and morbidity). Health risks from long-term exposure to PM2.5 are much greater than those from short-term exposure, and represent more than the cumulative impacts of repeated short-term exposures [23]. The epidemiological literature indicates that there is no safe level of PM exposure below which no population health effects are evident and that the change in risk per unit increase in exposure is generally larger at lower levels [24, 25]. It appears that all-cause mortality increases by about 7% for a 10 $\mu g/m^3$ concentration growth in long-term exposure, at least in areas with low-to-moderate levels of pollution [26]. If exposure is reduced, the elevated health risks appear to be at least partially reversible in the first few years after the reduction [27].

6.2.2. Heavy metals

Heavy metals contamination is one of the major threats to human population due to their toxicity, bioaccumulation and persistence level in the environment [28, 29]. Heavy metals contained on dust particles, particularly the fine ones, can be re-suspended into the atmosphere or absorbed by humans through ingestion, inhalation and dermal adsorption [30, 31]. The risk of heavy metals effect on human health is very high, because these metals have a tendency to be adsorbed, accumulated and biomagnified in the body and can be responsible for various diseases [32]. Metals have different poisoning effects on a human body corresponding to the nature of a particular metal. For example, As, Cd, Ni are classified by IARC as carcinogenic to humans (Group 1), Pb is classified as probably carcinogenic to humans (Group 2A), while Hg which is not classified as carcinogenic to humans (Group 3) can form organic compounds, such as methylmercury, which are possibly carcinogenic to humans (Group 2B) [17, 33]. According to the EPA, only chromium compounds should be classified as human carcinogens [34]. Generally, heavy metals have the potential to affect the neurological system, kidney function, ossification process and various other organs [35].

6.2.3. Polycyclic aromatic hydrocarbons

Over the last few decades, the interest in exposure to PM10-bound B[a]P and PM2.5-bound B[a]P has increased due to the fact that it can be associated with a broad range of health effects with a major impact on public health. Like particulate matter, benzo[a]pyrene is classified by IARC as carcinogenic to humans (Group 1) [17] and it has been recognized for many years as a good and sufficient indicator of human exposure to priority polycyclic aromatic hydrocarbons (PAHs) present in the air [13]. PAHs are inhaled in the form of vapor or together with dust particles with which they are associated and/or on which they are adsorbed. Depending on the fraction, dust particles may settle in different sections of the airways [36]. The smallest particles get into the alveoli, where substances adsorbed on them can get into the bloodstream and spread throughout the body. Larger particles, depending on their size, can settle in the bronchi, penetrate further as a result of diffusion and gravity or can be removed by the movements of epithelial cilia from the respiratory tract and along with the mucus enter the gastrointestinal tract [37]. PAHs have the ability to accumulate in adipose tissue due to their lipophilic properties. Studies show that benzo[a]pyrene accumulates in lung tissues, liver, spleen, kidneys, heart and skeletal muscle tissues. B[a]P and other congeners transformations occur mainly in the liver and the cholagogue system [38, 39]. As a result of their changes in the body, the metabolites formed have the ability to attach to DNA, RNA and proteins [40, 41] causing inhibition and errors in protein replication, transcription and biosynthesis [20, 42–44], and being one of the causes of cancer formation. PAHs can also penetrate into the body via the digestive system – along with the food intake, and through the skin [45, 46]. Until now, however, it has not been clearly established whether individual PAHs or their sum are responsible for the formation of neoplastic changes [47–49]. It is particularly difficult to assess the impact of PAHs adsorbed on particulate matter in the air, because individual hydrocarbons can react with other components emitted from incomplete combustion processes, causing a strengthening or weakening of their carcinogenic properties.

6.2.4. Non-Methane Volatile Organic Compounds

Non-Methane Volatile Organic Compounds (NMVOCs) are known for the adverse impact on human health even at trace levels [50]. A number of epidemiological studies have reported the incidences of detrimental impacts on health due to their toxicity, mutagenicity and carcinogenicity [51, 52]. The exposure to VOCs can have acute and chronic effects on health due to their chemical diversity which includes non-carcinogenic (sensory irritation, respiratory disorders, liver-kidney impairment) and carcinogenic (lung, blood, kidney and biliary tract cancer) effects [53–55].

6.2.5. Nitrogen oxides

The interest of many researchers in nitrogen oxides is due to the fact that they are some of the more dangerous components of the polluted air. The epidemiological data indicate that even low doses of NO_2 can cause an irritation of the throat and oral mucosa, as well as conjunctiva, which can lead to tracheobronchitis and other non-allergic respiratory diseases (bacterial and viral lung infections). It can also induce airway hyper-responsiveness and oxidative stress, which leads to the onset of asthma or its exacerbation [56, 57]. High concentrations of NO_2 in ambient air promote the occurrence of respiratory, cardiovascular and cerebrovascular diseases and increased mortality [58–60].

6.2.6. Sulfur dioxide

Significant effects of atmospheric sulfur dioxide on the human health include breathing difficulty, pulmonary oedema, eye irritation, cardiopulmonary diseases and an increase of mortality rates [61–63]. It has been found that hospital admissions for cardiac problem and mortality increase on the days with higher SO_2 concentrations [63]. The adsorption of SO_2 on inhalable particles is also considered to be an allergen, which can lead to asthma [64]. It should be mentioned here that some people are completely unaffected by concentrations of sulfur dioxide that lead to severe bronchoconstriction in others.

6.2.7. Carbon monoxide

Carbon monoxide is a gas extremely dangerous and highly toxic to humans. It causes severe poisoning. The brain is the most sensitive to it. About 80% of air contained in CO is bound to hemoglobin in the blood to form carboxyhemoglobin (COHb), which is unable to carry oxygen, leading to tissue hypoxia. With a content of about 20% COHb in the blood, there may be a decrease in vigilance and discrimination, drowsiness, confusion and, finally, coma and death may occur. After long exposure under high CO concentrations, damage to the myocardium may also occur [65].

6.2.8. Ground-level ozone

Ozone is a highly reactive (oxidising) compound present in both the urban and rural areas. It is not emitted directly but is formed when precursors react in the atmosphere in the presence of sunlight. There is good evidence supporting a causal relationship between the exposure to tropospheric (ground-level) ozone and respiratory effects, and a likely causal relationship with cardiovascular effects and total mortality [66].

After inhalation, ozone reacts with lipids, proteins and antioxidants in the epithelial lining fluid of the respiratory tract, creating secondary oxidation products. Initial ozone exposure leads to physiological reactions that may induce a host of autonomic, endocrine, immune and inflammatory responses throughout the body at the cellular, tissue and organ level. In addition, recent evidence indicates that short-term exposure to ozone is likely to induce metabolic effects. There is also some evidence that ozone exposure can affect the cardiovascular and nervous systems, reproduction, development and mortality, although there are more uncertainties associated with the interpretation of the evidence for these effects [66].

There are also some other adverse results that can be collectively ascribed to the air pollutants. Besides their (e.g. PM, SO_2 and NO_2) harmful physiological and adverse health effects, air pollution also results in poor visibility, triggering depression and severe psychological pressures [67]. Air pollutants, especially PM, may greatly increase the risk of suicide attempts [68] or suicides [69]. High concentrations of PM10 and NO_2, NO_x, SO_2 and CO may contribute to an increase in diabetes in children [70]. Similarly, high concentrations of PM2.5, NO_2 or ozone cause higher mortality in the group of people with diabetes [71]. It has also been proved that high concentrations of PM2.5 can contribute to an increase in the incidence of strokes [72]. Increased osteoporosis incidences have been demonstrated in the group of people exposed to high concentrations of PM1, PM2.5, PM10 and NO_2 for an extended period of time [73].

6.3. Sources of air pollution

In Europe, the production of goods is a key part of manufacturing activities and takes place in large and small factories. It also extends to the agriculture, which is important both because of its scale and the associated pollution risks. Complex industrial activities as well as simple assembly operations are usually associated with direct emissions of hazardous substances into the air. They appear in all production sectors, although some sectors are more strongly related to the emissions of some pollutants than others. For example, in 2020 in Europe, residential, commercial and institutional energy consumption, the manufacturing, the extraction industry and agriculture were the principal sources of particulate matter, both PM10 and PM2.5. On the other hand, agriculture was the principal source of ammonia and methane responsible for 94% and 56% of total emissions, respectively. Road transport was the principal source of nitrogen oxides (responsible for 37% of emissions), and the energy supply sector was the principal source of sulphur dioxide (responsible for 41% of emissions). The manufacturing and extraction industries were responsible for lead, cadmium, mercury and arsenic emissions in the amount of 60%, 54%, 44% and 42% of total emissions, respectively, and the energy supply sector for arsenic and mercury in the amount of 39%

and 38% of total emissions, correspondingly. Ultimately these branches create the principal sources of total heavy metals emissions, whereas the manufacturing and extractive industry sector (47%), and agriculture (27%) were the main source of NMVOCs. Energy consumption in the residential, commercial and institutional sector is the main source of CO and black carbon (BC) emissions, contributing to 46% and 37% of total emissions, respectively. The residential, commercial and institutional sector is also the primary source of B[a]P emission, responsible for 85% of it.

Over the years (2005–2020), the EU has reduced emissions of the main air pollutants, though at very different levels depending on the type of pollutants. Emissions of ammonia, for which 94% of emissions are generated by the agricultural sector, remain worryingly flat and have even increased in recent years in some Member States (Fig. 6.4). By contrast, emissions of sulphur dioxide (SO_2) fell significantly from 2005 to 2020, with a decrease of 79%. This was mainly due to the reduced use of coal over the period. Major reductions were also seen for nitrogen oxides (NO_x), black carbon (BC), carbon monoxide (CO) and non-methane volatile organic compounds (NMVOCs), with declines of 48%, 46%, 42% and 31%, respectively [74].

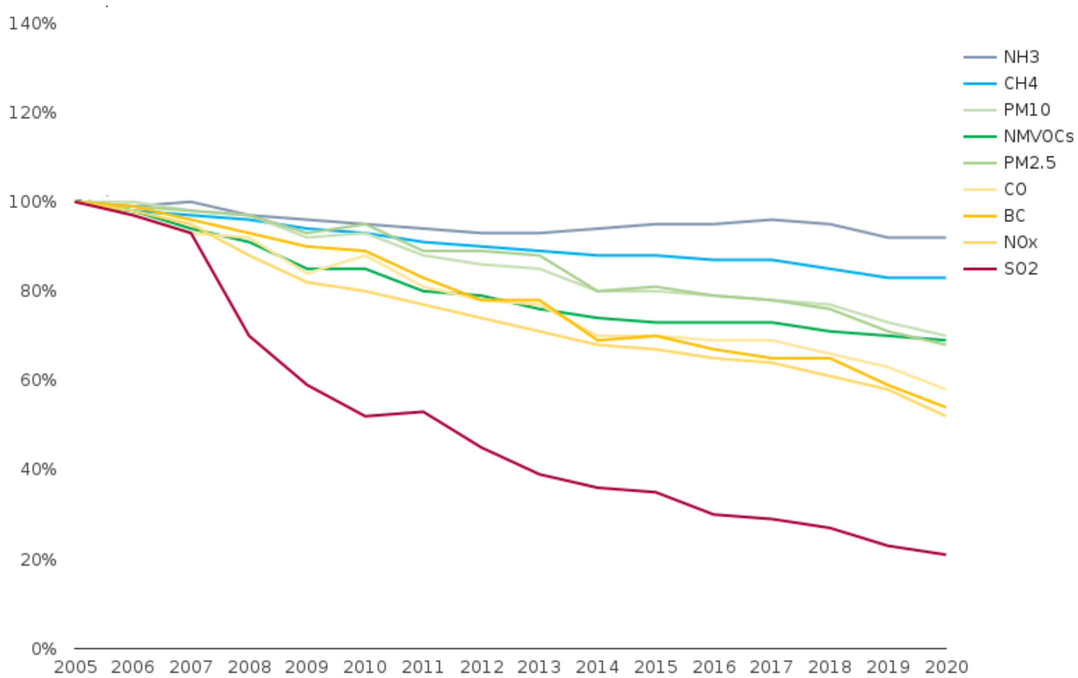

Fig. 6.4. Trend in EU Member States emissions, 2005–2020 [74]
Rys. 6.4. Tendencje w emisjach zanieczyszczeń powietrza w latach 2005–2020 w państwach członkowskich UE [74]

6.4. Air quality standards

Air quality in Europe has much improved since the EU first started to tackle this issue in the 1970s. Concentrations of basic pollutants have been significantly reduced since then. Starting in the 1980s, the EU has adopted strict policies on air quality. The EU's Ambient Air Quality Directives set air quality standards for substances such as PM10, PM2.5, nitrogen oxides, sulfur dioxide, carbon monoxide, lead, B[a]P, benzene, ozone. These directives also define common methods of monitoring (reference methods), assessing and informing the public on ambient air quality in the EU. The European Commission has proposed an updated "Directive on ambient air quality and cleaner air for Europe" [75]. In turn, on October 2022, as part of the European Green Deal, the Commission has proposed to revise the Ambient Air Quality Directives. The revision aligns the air quality standards more closely with the recommendations of the WHO [76]. As a consequence, the zero pollution state for air is supposed to be achieve by 2050. To help diminish the sizeable health burdens from pollutants, the WHO provides air quality guidelines, while many countries and regions also have their own standards (Tab. 6.1). The EU air quality standards are generally less strict for all pollutants than the new health-based air quality guidelines that were published by the WHO in 2021. The same can be said about the majority of other countries. For instance, in some regions of the world, the air quality standard is still determined by total suspended particulate matter (TSP) concentration, while it is well known that particulate matter with an aerodynamic diameter of less than 10 μm is the most hazardous. For many substances standards have not been set outside UE. It is also often the case that the permissible concentrations of pollutants are high, and their levels are not always met.

6.5. Ambient air quality

Poor air quality is a problem in almost all developed and developing countries. However, people in low- and middle-income countries are the most at risk. High concentrations of air pollutants are common in industrial regions, especially with specific topography, as well as in heavily urbanised areas. WHO estimates that nine in ten people worldwide are breathing highly polluted air. Despite efforts to reduce air pollution in many countries, there are regions, notably Central and Southern Asia and Sub-Saharan Africa, in which populations continue to be exposed to increasing levels of air pollution. The majority of the world's population continue to be exposed to levels of air pollution substantially above WHO Air Quality Guidelines. The most polluted countries in the world include: Bangladesh, Chad, Pakistan, Tajikistan and India, of which the capital was recognised as the most polluted capital of the world for the fourth year in a row, right behind New Delhi [77]. The other countries with entries on the list of the most polluted cities are Saudi Arabia, Bhutan, Serbia, Cameroon and Egypt. The highest number of deaths/illnesses could be attributed to ambient fine particulate matter air pollution, or PM2.5. PM2.5 comes from a wide range of sources, including energy production, households, industry, transport, waste, agriculture, desert dust and forest fires and particles can travel in the atmosphere for hundreds of kilometres and their chemical and physical characteristics may vary greatly over time and space [78].

It is observed that air quality in Europe is better compared to previous years (Fig. 6.5). This also results in a reduction of the negative impacts on human health. Moreover, the decrease in pollution is showing a long-term trend due to the implementation of policies that reduce emissions and improve air quality (joint action taken by the EU and national, regional and local authorities). Nevertheless, exceedances of the daily limit value recommended by the EU for PM10 (50 $\mu g/m^3$ – Tab. 6.1) occur throughout the continent. The highest concentrations are observed in Northern Italy, Croatia, Bulgaria, Serbia, Kosovo, Turkey, Bosnia and Herzegovina, North Macedonia and Poland [74, 79]. Unfortunately, Poland is considered a country with one of the most serious problems related to air pollution in the EU, mainly PM2.5, PM10 and the concentration of benzo[a]pyrene is one of the highest in Europe (Fig. 6.5).

In 2021, the majority of the urban population in the EU was exposed to levels of key air pollutants that have ability to damage human health (see Fig. 6.5). In particular, 97% of the urban population was exposed to concentrations of fine particulate matter (PM2.5) above the new WHO guideline level of 5 $\mu g/m^3$ (Tab. 6.1).

6.6. Greenhouse gas emissions

The International Panel on Climate Change (IPCC) estimates that global greenhouse gas emissions (GHG) come from the transport (14%), energy, including generation of electricity and heat (35%), industry (21%) and buildings (6%) and agriculture, forestry and other land use (24%) [85]. The concentration of GHG in the atmosphere causes global temperatures to rise with a host of impacts and catastrophic consequences. It is wreaking havoc across the world and threatening lives, economies, health and food. The world is far from securing a global temperature rise to below 2°C as promised in the Paris Agreement.

Table 6.1
Recommended air quality guideline (AQG) levels by EU and WHO; air quality standards in selected countries

Pollutant	Aver. time	Guideline value							
		WHO [76]	EU [80]	Afghanistan [81]	Australia [82]	Japan [82]	Jordan [82]	Egypt [82]	South Africa [83]
PM2.5 [μg/m^3]	Annual	5	20	35	8	15	15	90 (TSP)	
	24-hour	15		75	25	35	66	230 (TSP)	
PM10 [μg/m^3]	Annual	15	40	70	20	100 (TSP)	70		40
	24-hour	45	50	150	40–50	200 (TSP)	120	70	75
NO_2 [μg/m^3]	Annual	10	40	40	60		50		40
	24-hour	25		80		75–115	80	150	
	1-hour	200	200		230		210	400	200
O_3 [μg/m^3]	Peak season	60			200 (1 h)				
	8-hour	100	120	100	160 (4 h)		120	120	120
SO_2 [μg/m^3]	24-hour	40	125	50	210	106		150	125
	1-hour		350		530	226		350	350
	10-minute	500							500
CO [mg/m^3]	24-hour	4							
	8-hour	10	10	10		23		80	
	1-hour	35		30				30	
	15-minute	100							
C_6H_6 [μg/m^3]	Annual		5			3			5
B[a]P [ng/m^3]	Annual	0.12	1						
Pb [μg/m^3]	Annual	0.5	0.5	0.5	0.5		0.5	1	0.5

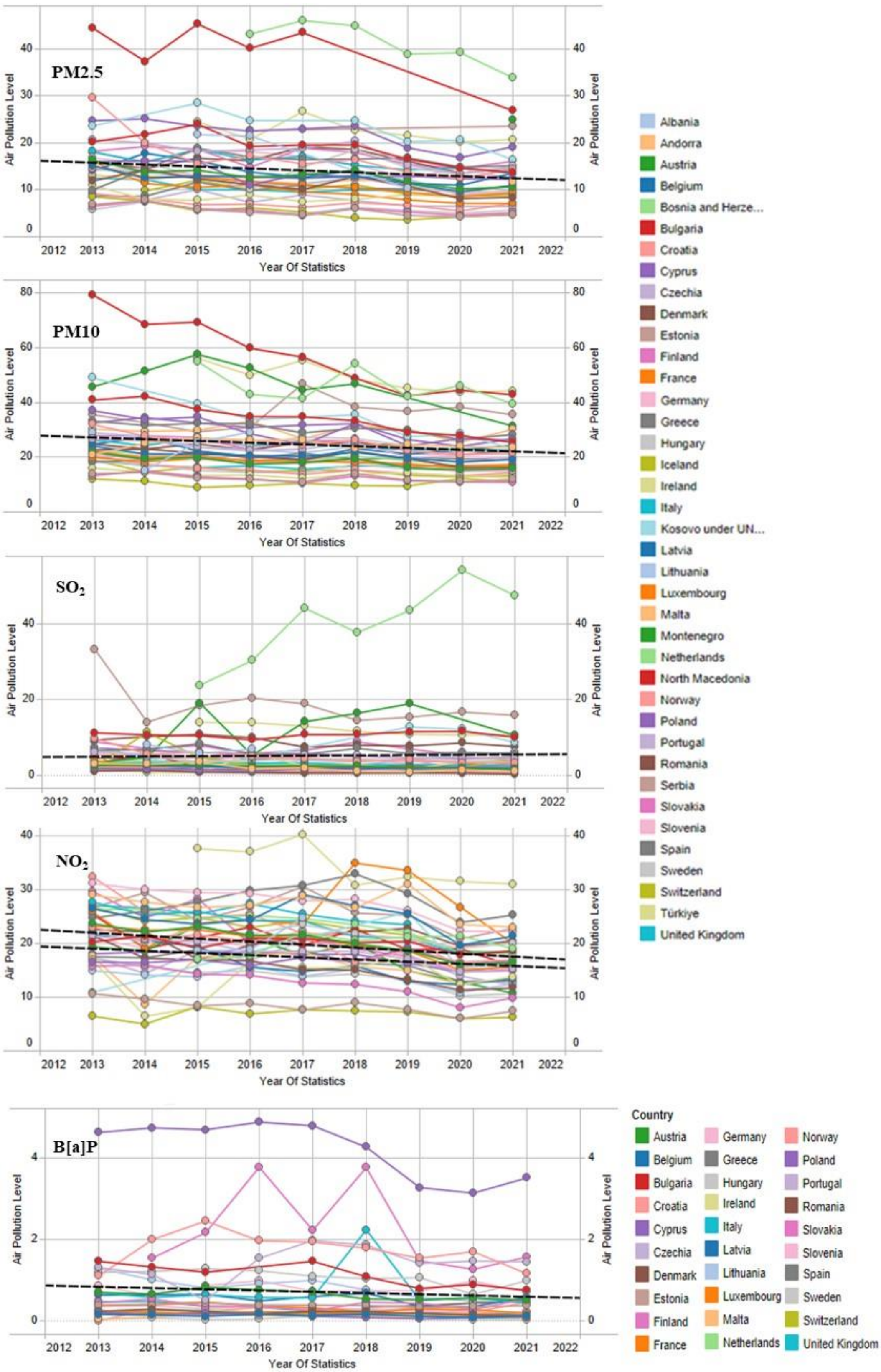

Fig. 6.5. Average annual concentrations of NO_2, SO_2, PM2.5, PM10 [µg/m^3] and PM10-bound B[a]P [ng/m^3] in European Countries from 2013 to 2021 [84]

Rys. 6.5. Średnioroczne stężenia NO_2, SO_2, PM2.5, PM10 [µg/m^3] i B[a]P związanego z PM10 [ng/m^3] w krajach europejskich w latach 2013–2021 [84]

Table 6.2

The top greenhouse gases (GHG) emitters in 2018 [86]

No.	Country	Emissions [million Mg of GHG]	As percent of global [%]	Per capita [Mg of GHG]
1.	China	13 739,79	27.8	9.71
2.	United States of America	6 297,62	12.7	19.27
3.	India	3 619,80	7.3	2.67
4.	Russian Fed.	2 323,74	4.7	16.07
5.	Japan	1 270,21	2.6	9.99
6.	Brazil	1 259,51	2.5	5.97
7.	Indonesia	1 074,19	2.2	4.03
8.	Islamic Rep. of Iran	926,37	1.9	11.30
9.	Germany	873,60	1.8	10.62
10.	Mexico	801,38	1.6	6.13
11.	Canada	762,14	1.5	20.62
12.	Rep. of Korea	758,14	1.5	14.82
13.	Saudi Arabia	750,60	1.5	22.37
14.	Australia	581,97	1.2	23.49
15.	Türkiye	579,19	1.2	7.07
16.	South Africa	573,96	1.2	10.00
17.	Pakistan	504,59	1.0	2.51
18.	United Kingdom	463,74	0.9	6.97
19.	France	450,39	0.9	6.90
20.	Thailand	434,78	0.9	6.28
21.	Poland	424,96	0.9	11.15

Table 6.3 shows the top GHG emitters in 2018 in the world. They account for almost 80% of global emissions. Among them, China is one of the top emitters. It accounts for 27.79% of global emissions. In 2018, it emitted 13,739.79 million tonnes of GHG. The United States emits half as much, i.e. 6,297.62 million tonnes. Among European countries, the highest emissions were recorded in Germany, United Kingdom, France and Poland. In 2018, they emitted 873.60; 463.74; 450.39 and 424.96 million tonnes GHG, respectively. On the other hand, Qatar is one of the countries with the highest GHG emissions per capita – 66.23 tonnes. Saudi Arabia, Oman and Australia are next in order with 29.09, 24.85 and 23.49 tonnes GHG emissions per capita, respectively. With a baseline in 1990, some countries are emitting more GHG, some the same and others are emitting less. The largest increase in GHG emissions has been recorded in

countries such as United Arab Emirates, Malaysia, Oman, Viet Nam, Mozambique, Qatar, (above 250%) and Chad (579%). However, the situation is the worst in Equatorial Guinea. In this country, GHG emissions increased by as much as 6169%. Whereas, Dem. People's Rep. of Korea, Ukraine, Moldova have had one of the biggest drops in GHG emissions at approx. 70% and Denmark, Latvia, Romania, United Kingdom at about 30–55% [86].

It is also worth noting that transport represents almost a quarter of Europe's GHG emissions and is the main cause of air pollution in the cities. The transport sector remains one of the only sectors of the EU economy where emissions are still above 1990's levels. Within this sector, road transport is by far the biggest emitter accounting for more than 70% of all GHG emissions from transport in 2019 [85].

6.7. Air quality improvement

The world needs to cut GHG emissions by 30 gigatonnes annually by 2030 in order to limit temperature rise to 1.5°C and thus halt frequent extreme weather events in the near future like floods, droughts, wildfires and hurricanes. And the emission reductions of CO_2 and other GHGs need to start happening now.

Some of the same pollutants contribute both to climate change and local ambient and household air pollution. For example, black carbon, produced by inefficient combustion in sources such as cookstoves and diesel engines, is the second greatest contributor to global warming after carbon dioxide [77]. Black carbon is also a significant contributor (between 5% and 15%) of urban exposure to PM2.5. The third largest contributor to global warming is methane, which reacts with other pollutants to form ozone. Both of these pollutants are short-lived in the atmosphere, meaning that targeting them for removal would have immediate beneficial effects on both climate change and non-communicable diseases. A set of practical interventions, from replacing polluting cookstoves with cleaner household energy solutions to replacing the most polluting diesel fuels and engines with less polluting ones, would prevent approximately 0.5°C of global warming, and save some 2.5 million lives a year by 2050 [85].

In the transport sector, an accelerated transition from diesel and petrol engines to electric powered vehicles would contribute to reducing emissions of local air pollutants and greenhouse gases. Much greater health gains would result from replacing short urban car journeys with walking and cycling, due to increases in physical activity.

The dominant sources of electricity generation today are conventional large-scale power plants using fossil fuels. Coal and oil produce high levels of both GHG emissions and fine particulate matter. It is possible to mitigate fossil fuel emissions somewhat through technological solutions (e.g. carbon capture and storage), but the benefits are likely to be smaller than those from switching away from coal and oil to other energy sources, namely by increasing the share of natural gas, nuclear power and renewables in particular.

More sustainable agricultural production measures, such as reducing open burning of agricultural land, would help mitigate climate change and reduce air pollution in some regions. Even greater gains may be obtained by reducing human consumption of meat and by reducing food waste. Even though meat and dairy make a relatively small contribution to overall human energy intake, around 60–80% of the greenhouse gas emissions from agriculture come from the livestock sector [87].

Consumers can also perform an important role in improving ambient air quality by choosing more sustainable products and services. They can do this by buying locally sourced products that do not require long-distance transport which leads to greenhouse gas emissions. They can also choose products and services that have been made using environmentally friendly production processes.

6.8. Summary

According to the World Health Organization, air pollution is the greatest environmental threat to public health, causing numerous diseases, including those of cardiovascular, respiratory, nervous and endocrine systems, lung cancer, fertility problems or acceleration of neurodegenerative processes. Its influence on human's health has the countable cost as it leads to lost working days and high healthcare costs. Air pollution has also a negative influence on water and soil quality, and harms ecosystems. It strongly affects several branches – agriculture and forests as well as material and buildings industry. In order to prevent the described phenomena, numerous actions are taken to protect the air. Cooperation with global, European, national and local partners from the health sector and decision makers at various levels is needed. The most important goal is to reduce the number of diseases and deaths caused by polluted air, as well as to protect the most vulnerable people. The EU has three different legal mechanisms to manage air pollution: defining general air quality standards for ambient concentrations of air pollutants; setting national limits on total pollutant emissions; and designing source-specific legislation, as for example to control industrial emissions or set standards for vehicle emissions, energy efficiency or fuel quality. This legislation is complemented by strategies and measures to promote environmental protection and its integration into other sectors.

While air pollution in Europe has generally decreased in recent decades, the EU's aspirations to achieve air quality at levels that do not have significant negative impacts on human health and the environment, still remain unattained. Air quality does not comply often with the EU standards, especially in urban areas – where the majority of people live. This global tendency touches in the special way the most problematic pollutants today that are fine particles, nitrogen oxides and ground-level ozone.

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7. INDOOR ENVIRONMENT AND SUSTAINABLE BUILDINGS

Together with other industries, the developing construction industry is trying to meet the challenges of sustainable development from an environmental, social and economic point of view [1]. Sustainable building includes both the structure and the use of processes that are environmentally friendly and resource efficient throughout the life cycle of the building, including energy use, water use, indoor environmental quality, material selection, stormwater infiltration and energy management in the building. All these processes are considered from the design and construction stages through maintenance and renovation to demolition.

The indoor environment quality (IEQ) is an integral part of sustainable construction and refers to the conditions inside the building, i.e. air quality (IAQ), which focusses on airborne pollutants, as well as other issues related to health, safety and comfort, such as aesthetics, ergonomics, acoustics, lighting and electromagnetic fields. When planning cost-effective buildings, it is easy to forget that the success or failure of a project can depend on the quality of the indoor environment. People spend more than 90% of their time indoors and, given the recent COVID-19 outbreak, indoor air quality is more closely related to occupant health [2–4]. Healthy, comfortable occupants are often happier and more productive. Unfortunately, this simple truth is often forgotten because it is easier to focus on the cost of construction than to determine the value of increased productivity and user health. However, even a small percentage increase in efficiency multiplied by the number of employees can build up significant savings.

People engaged in the design and construction of buildings today also face the challenge of predicting and designing for uncertain and rapidly changing climatic conditions. From an environmental point of view, one of the main threats, also noticeable in Poland, is the installation of air conditioning systems in anticipation of global warming, a strategy that itself contributes to energy consumption and related greenhouse gas emissions. As the researchers noted, technologies and design features considered efficient today may not be the same if the climate changes. Similarly, the currently comfortable buildings may be completely unsuitable for future conditions. Much depends on the pace and extent of change, and economic and environmental modelers are already exploring a range of possible scenarios. In practice, much also depends on whether and how people's perception of comfort evolves [5].

7.1. Sustainable building and IEQ standards

A sustainable building (better known as a green building) is an economical, comfortable and environmentally friendly building. By designing, constructing and using green buildings, we simultaneously meet our current needs and ensure that future generations can meet their future needs [6].

The World Green Building Council defines a green building as one that reduces or eliminates negative impacts during design, construction or operation and can have a positive impact on our climate and natural environment [7]. The challenge facing green buildings is not only the technical need to reduce the consumption of energy, water and raw materials, but above all to provide a sustainable place for people to live in [8]. In addition to building construction and equipment needed for it, the use of intelligent control systems can contribute to the sustainable development of buildings. A smart system is an electrical grid that includes smart meters, appliances and renewable energy control systems that can communicate with each other and offer users valuable information about their status. In this way, users can control the production and distribution of energy more consciously and change their behaviour [8]. The most important features of sustainable buildings are shown in Figure 7.1.

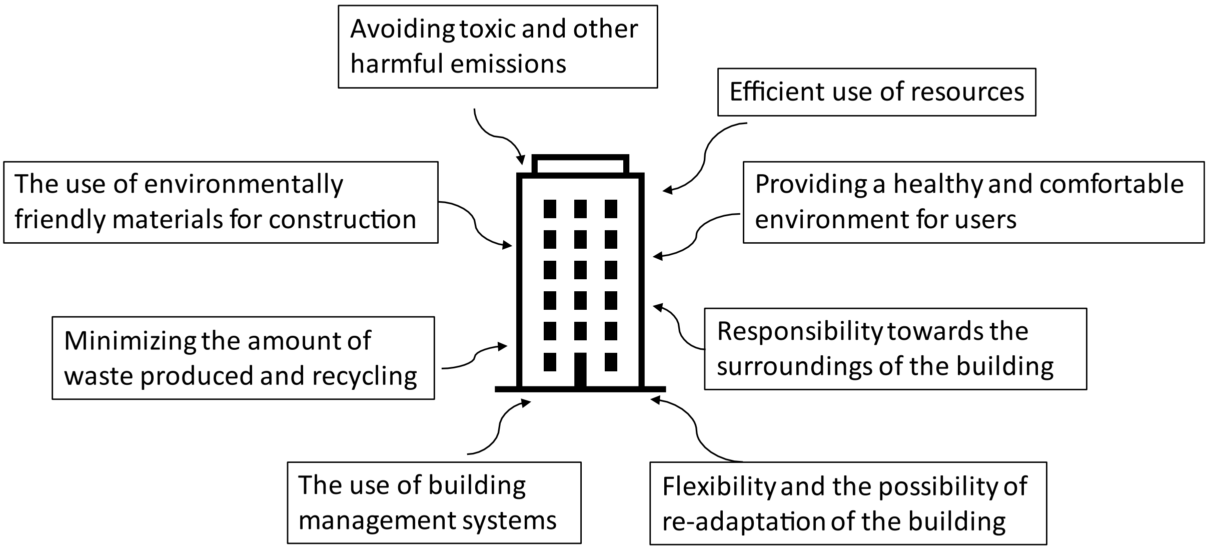

Fig. 7.1. Features of sustainable buildings [6]
Rys. 7.1. Cechy zrównoważonego budynku [6]

The green building methodology is a well-established and clearly defined strategy to achieve sustainable environmental impacts in different climates in response to global challenges in energy and health. Various organisations and agencies have proposed rating indicators for both new and existing buildings (Tab. 7.1). These indicators have similarities and differences. They have been proposed by various countries and institutions in relation to building types, goals and scoring rules. Some standards are mandatory for national or regional implementation, while others are voluntary or recommended. Some standards only focus on indoor air, while others govern other requirements, such as water and energy. Normally, mandatory standards provide a minimum guarantee and a basic level of population health [10].

Table 7.1

Information on standards and certifications [10]

Standard/Certification	Public. year	Public. region	Applicable building type
Ventilation for Acceptable IAQ (ANSI/ASHRAE Standard 62.1–2016)	2016	US	Not specified
Ventilation for Acceptable IAQ (ANSI/ASHRAE Standard 62.1–2019)	2019	US	Not specified
Leadership in Energy and Environmental Design (LEED v4)	2019	US	Commercial, retail, hotel and residential
WELL Building Standard v2.2022.Q2 (WELL)	2022	US	Not specified
Building Research Establishment Environmental Assessment Method (BREEAM)	2016	UK	Non-residential
Haute Qualité Environnementale (HQE)	2016	France	Non-residential and residential
Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB)	2020	German	Non-residential
Guide from MHLW	2000	Japan	Not specified
Comprehensive Assessment System for Built Environment Efficiency (CASBEE)	2014	Japan	All except detached houses
Air quality guidelines global update 2005 (AQG 2005)	2005	International	Not specified
WHO global air quality guidelines (AQG 2021)	2021	International	Not specified
WHO guidelines IAQ: selected pollutants	2010	International	Not specified
ZIELONY DOM	2021	Poland	Residential
EN 16798-1:2019-06	2019	EU/Poland	Residential and non-residential

Some of the best-known IEQ standards are developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), an independent, private non-profit organisation. For example, ANSI/ASHRAE Standard 62.1–2019 [11] focuses on indoor air and is considered the fundamental reference for ventilation within the acceptable IAQ range. In turn, the European standard EN 16798-1:2019-06 [12] contains guidelines for the input parameters of the indoor environment for the design and assessment of the energy performance of buildings, taking into account the indoor air quality, thermal environment, the lighting and acoustics [10].

In addition to the standards, certificates have also been developed that promote buildings to a higher level. The world’s first green building rating system, the “Building Research Institute Environmental Assessment Method” (BREEAM) [13], was developed in Great Britain. The United States has implemented a complete “Leadership in Energy and Environmental Design” (LEED) [14] rating system that has different regulations for different types of buildings and stages. Japan relies on the standardised rating system “Comprehensive Building Environmental Performance Assessment System” (CASBEE) [15] to promote the development of green buildings. Among the European certificates, there are also French HQE [16] and German DGNB [17]. The development of these rating systems has contributed significantly to energy savings in buildings and to the reduction of greenhouse gas emissions [10]. The WELL Building Standard certification system [18] has also appeared in the housing market, referring to the attributes of a building that have the greatest impact on the health of the users.

In Poland, in 2021, the ZIELONY DOM certificate for residential buildings was introduced, developed by the Polish Green Building Council (PLGBC) [6]. To receive this certificate, the residential building must meet a number of criteria. The building itself is assessed, along with the way it was designed and constructed or the arrangement of the surroundings.

The answer to the idea of sustainable buildings is also the introduction of regulations that tighten the requirements regarding the amount of energy consumed by newly built buildings (e.g. in accordance with Directive 2010/31/EU [19] from January 2021, all newly built buildings should be characterised by almost zero energy consumption – the directive does not provide clear numerical criteria). In this way, the emission of greenhouse gases, which is of great importance in the degradation of the natural environment, will be limited.

7.2. IEQ factors

IEQ factors affect the satisfaction, health and well-being of building occupants [20]. Each IEQ factor is affected by different parameters. Most factors and IEQ parameters affect both occupant satisfaction and energy consumption in buildings [21], but to varying degrees. The two main IEQ factors that have the most significant impact on occupant satisfaction, thermal comfort and quality of the indoor environment.

7.2.1. Thermal comfort

Thermal comfort is a state of mind that expresses satisfaction with the thermal environment but is a subjective assessment [22]. People who feel thermally comfortable inside a building usually refer to their feeling of comfort in a room, e.g. the room is hot, cold or neutral. It is not a direct sense of room air temperature [23]. The thermal comfort model is a key element in the design, operation and optimisation of a building [24]. A low level of thermal comfort usually leads to reduced efficiency, deterioration of health and low thermal satisfaction of the occupants [25]. The use of appropriate technical building equipment, such as heating, ventilation and air conditioning (HVAC) systems, ensures thermal comfort. The choice of a specific solution and the way it is used have an impact on the energy consumption. On average, more than 50% of the energy used in a building is used by the HVAC system [26]. The construction of external partitions (thermal insulation, glazing) and the conditions outside (air temperature, wind, solar radiation) also have a large impact on energy consumption. The building construction and the environmental conditions in the room are, therefore, interrelated; thus, when evaluating the energy consumption of the building, it is necessary to verify the maintenance of the assumed indoor conditions at the same time. This comprehensive approach is in line with the energy performance of buildings directives.

Maintaining thermal comfort requires balancing the heat generated by metabolism with the heat lost by the body. Thermal comfort can be determined by evaluating six main parameters, four of which are related to the environment, while the other two are related to people. Ambient parameters include relative humidity, air temperature, airflow velocity and mean radiant temperature, and human parameters include type of clothing and levels of activity [25]. Models have been developed to assess thermal comfort. The best-known predicted mean voice (PMV) was based on heat balance principles and collected data in a stable climate-controlled environment. This model has been adopted by standards such as EN ISO 7730:2006 [27], ASHRAE 55 [22] and EN 16798-1:2019-06 [12], which are commonly used by engineers to define and design the thermal environment in buildings. These standards are intended to define conditions that ensure the comfort of all healthy adults in a room. The optimal state according to this model, defined as thermally neutral, is a situation in which the person prefers neither a cooler nor a warmer environment.

Although the importance of the PMV model has been proven in many studies, it turned out that the PMV model did not perform very well in assessing thermal comfort in naturally ventilated buildings. Recent studies [28, 29] indicate that there are discrepancies between the prediction of the PMV model and the vote of users when assessing the indoor thermal comfort. This led to the development of an adaptive model for assessing thermal comfort as a tool to extend the PMV method in buildings with natural ventilation [30, 31]. The basic assumption of this model is that people can adapt to a changing thermal environment by using various adaptation possibilities. Using adaptive comfort temperature as the set point of room temperature potentially reduces the utilisation of the HVAC system. Savings result mainly from the acceptance of higher temperature values in rooms than those recommended in summer periods and lower than those recommended in winter periods [32]. In situations or locations where the use of an HVAC system is unavoidable, a wider range of the thermal environment acceptability will lead to lower energy consumption [33].

7.2.2. Indoor air quality

A heavily polluted indoor environment can significantly impair the health of users; therefore, evaluating indoor air is crucial [21]. The operation of buildings emits significant amounts of pollutants that can have negative health effects, such as asthma, lung cancer and premature death. Typical measurable indicators of air quality are CO_2, VOCs and PM2.5 [34]. Ventilation systems can facilitate the transmission of infectious diseases through air. In other words, infectious diseases can be transmitted through a poorly ventilated indoor environment. One of the assessment criteria is the determination of ventilation airflow. There is a relationship between ventilation airflow per person staying in the room and the percentage of people dissatisfied with air quality. This relationship was developed in studies where humans were the main source of pollution [35, 36].

The selection of appropriate construction materials has been identified as one of the main problems related to IAQ [37]. When designing and renovating buildings, both the quality and quantity of the materials used and their impact on the environment should be taken into account [38].

The maximum allowed concentrations of pollutants in the indoor air are defined for the sake of the health of the occupants. Standards and guidelines published by organisations such as World Health Organization (WHO) [39], Occupational Safety and Health Administration (OSHA), or National Institute for Occupational Safety & Health (NIOSH) publish recommended permissible concentrations of pollutants. The most common pollutants, the limits of which are provided in the standards, include carbon monoxide, nitrogen dioxide, radon and volatile organic compounds (such as benzene, formaldehyde, naphthalene and benzo(a)pyrene). These compounds cause health effects negative for humans. In Poland, in the case of workplaces, the problem of acceptable levels of pollutants in the indoor air is regulated by the Regulation of the Minister of Family, Labour and Social Policy on the maximum acceptable concentrations and intensities of factors harmful to health in the work environment [40]. In the case of other environments intended for permanent residence of people, the Ordinance of the Minister of Health and Social Welfare on acceptable concentrations and intensities of factors harmful to health, emitted by building materials, devices and equipment in rooms intended for people [41] was announced.

However, in many cases, even though recommended concentrations of pollutants are not exceeded, air quality is not accepted by a large group of people. This is due to the odour properties of a large group of compounds, mainly of volatile organic compounds with an unpleasant odour. For some of these compounds, acceptable concentrations have not been determined due to the lack of harmful effects on humans.

7.3. Life cycle assessment

The need to conduct environmental, economic and social research in the construction sector forced the introduction of methodologies and parameters that quantitatively describe the impact of a product or process, in this case a building, on the environment and people, these are [1]:

- environmental life cycle assessment (ELCA),
- life cycle costs (LCC),
- social life cycle assessment (SLCA).

The environmental objective of building sustainability has been evaluated mainly by considering an impact category, such as carbon footprint and/or energy use, or both [42]. For economic purposes, the LCC of buildings is widely considered in the literature [43], but the economic impact from the perspective of stakeholders, that is, developers and end-users, has not yet been explicitly discussed. The SLCA's building research addresses key components of sustainability, including intergenerational social equity [44]. Although these sustainability tools (ELCA, LCC, and SLCA) are fair enough to address a single sustainability goal throughout the lifetime of buildings, integrating these tools to determine the overall sustainability rating of a building would be very useful [45].

7.3.1. Environmental life cycle assessment

From the point of view of the ELCA methodology, buildings are products, so the environmental assessment should be carried out for entire facilities. Hundreds of individual products and processes must be considered, which are also interrelated (for example, the type of insulation affects the heat demand). Such a detailed analysis makes it possible to determine the overall environmental effect. Additionally, the ELCA methodology imposes an assessment throughout the life of a product or a process, that is, from the cradle to the grave, starting from the extraction of raw materials, through production, processing, distribution, use, repairs, maintenance and disposal [46].

The complexity of buildings and the ELCA methodology that covers their entire life cycle make the determination of environmental impacts complicated. The long operating periods of buildings cause the assumptions made during the LCA analysis to be highly uncertain. These include, for example, the frequency of replacements and renovations, the technologies used in them, the number of users (residential buildings are often used for two generations), changes in construction techniques. The complexity of building objects causes difficulties at the stage of analysing the set of inputs and outputs and processes related to the stages of the life cycle. The LCA methodology requires the compilation of environmental data for all products and processes, which is extremely laborious. Such data are currently available in Poland for a small number of products. Despite the complexity of the LCA analysis in the case of buildings, scientists are conducting research in this area. Most articles base their research on the IPCC structure [47], where the measure of the environmental impact of greenhouse gases is the global warming potential expressed in kg CO_{2e} [46].

7.3.2. Life cycle costing

In the construction industry, most financing decisions are often made on the basis of the initial investment cost, and when evaluating alternative building design alternatives, not only the initial cost, but also future operating costs should be considered. Some selected alternative may seem profitable at the construction stage, but be more expensive during the operation of the building. Choosing such an alternative will not be profitable in the long term [46].

Life cycle cost analysis can be used to assess the long-term cost-effectiveness of an investment. According to Ammar et al. [48] "the life-cycle cost of an item is the sum of all funds expended in support of the item from its conception and fabrication through its operation to the end of its useful life". LCC are the most commonly used model to assess the economic performance of a building or a specific building element over its lifetime. The general objectives of the LCC analysis have been identified by the Royal Institute of Chartered Surveyors [49], they are [46]:

- enabling a more effective assessment of investment options,
- considering the impact of all costs, not just the initial capital costs,
- facilitating the choice between competing alternatives.

The LCC analysis provides a much better assessment of the long-term cost-effectiveness of an improvement measure than alternative economic methods that focus only on the initial investment costs or operating costs in the short term [50].

The significance of using life cycle costing in the building sector has been confirmed at the regulatory level in Europe also by Directive 2010/31/EU [19], which established that Member States shall calculate "cost-optimal" minimum energy performance requirements using a methodology framework in accordance with the regulations and guidelines of the European Commission based on EN 15459:2007 [51]. The cost-optimal level means the level of energy performance that leads to the lowest cost over the estimated life cycle, where the lowest cost is determined taking into account energy-related investment, maintenance and operation costs, including energy costs and savings [52].

7.3.3. Social life cycle assessment

SLCA is a methodology to assess the potential social impacts of products throughout their life cycle [53]. The emphasis is on different categories of stakeholders (e.g. local communities, employees, children) who may be affected by the analysed systems. The greatest limitation of SLCA seems to be the availability of data, as the nature of social phenomena implies an inherent difficulty in obtaining objective quantification. This can be addressed by involving stakeholders and subject matter experts through questionnaires and interviews or using social risk databases [54].

7.4. Standard of buildings in Poland

In Poland, year-by-year there is an increase in the number of new buildings. According to the data of the Central Statistical Office (GUS) [55], in 2022, compared to the previous year, there was an increase in the number and area of flats commissioned for use and the area of non-residential buildings commissioned for use. Compared to the previous year, there was an increase in the number of flats by 1.7% and new residential buildings by 2.6%; 0.6% more new non-residential buildings were commissioned in 2022. The total usable floor space of new and extended non-residential buildings was 12.6% more than in 2021.

The design and erecting of buildings in Poland must comply with applicable legal acts. The most important act is the Construction Law [56]. Another important document is the Regulation of the Minister of Infrastructure on the technical conditions to be met by buildings and their location [57]. The regulation lists requirements for both the construction and technical equipment. Most buildings in Poland have traditional construction, in 2022 98.5% have been erected in this construction; only 1.1% of the erected buildings had a wooden structure [55]. The share of households in domestic energy consumption is significant; in 2021 it was 20.2%, placing Poland at the average European level [55]. In the structure of energy consumption in households in Poland, the most important are solid fuels, mainly coal (which is an exception in the European Union) and firewood. In 2021 they were most often used for space heating (by 32.8% of households). These fuels were also used to heat water (22.5% of households) and much less often to cook meals (1.7%). Renewable energy sources constitute a small percentage (3.5%), but their share is growing year by year.

An increasing number of buildings in Poland have a sustainable building certificate. According to the statistics of the Polish Green Building Association PLGBC [6], there is also a steady increase in the number of buildings certified in more than one multi-criteria certification system. Most often, it is a marriage of BREEAM or LEED with WELL, but there are also other combinations. In March 2023, more than 1600 buildings in Poland were already certified (Fig. 7.2). BREEAM maintains its leading position, reaching nearly 82% of the market share, while the share of all other certifications is decreasing. The Polish ZIELONY DOM, despite its "young age", has already gained a 1.6% market share (27 buildings). It should be noted that currently only buildings at the design stage are pre-certified under this system, while full certification is possible after the completion of the construction. BREEAM recorded an annual increase of 21% in the number of buildings. There were 235 buildings, which is one building less than in the previous year. There is a general trend toward stabilising the number of new certifications in this system to the level of over 200 buildings per year. The ratings obtained under the BREEAM system are at a very high level – Very Good, Excellent and Outstanding account for 84% of all ratings, which may demonstrate the high standards of certified buildings [6].

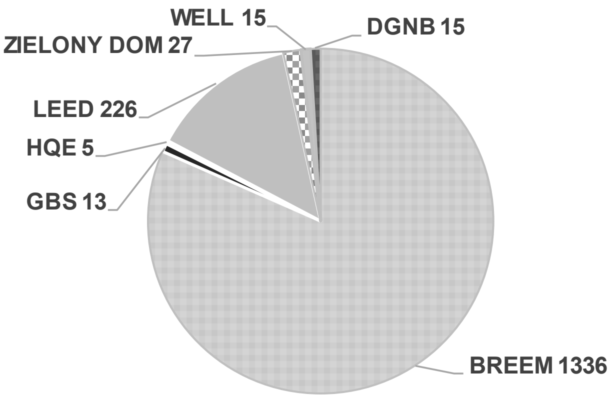

Fig. 7.2. Number of certified buildings in Poland [6]
Rys. 7.2. Liczba certyfikowanych budynków w Polsce [6]

In summary, it can be said that the market for certified buildings in Poland is still growing, which shows the growing awareness of sustainable development in the building industry.

7.5. Energy demand, global warming potential, and thermal comfort – examples for Polish buildings

One of the points of global climate and energy policy is the reduction of greenhouse gas emissions. Households use energy and it is the main driver of CO_2 emissions. Reducing energy consumption has a positive impact on both building operating costs and the environment. The building materials used to build the house are also an important factor. Materials with the lowest environmental impact in all phases of the life cycle should be used. Some investors decide to improve the insulation of external partitions beyond the minimum requirements; this results in a reduction in energy consumption for heating throughout the entire life cycle, i.e. a reduction in the building's operating costs. In well-insulated buildings, the problem of overheating can occur during summer periods. Such a building heats up more slowly, but if it gets very hot, it is more difficult to cool it down, for example, at night. In buildings with mechanical cooling systems, this situation can result in increased demand for cooling; in buildings with natural ventilation, this can result in deterioration of thermal comfort. The problem of buildings overheating with an increasing demand for cooling will increase with the warming climate. The results of two studies confirming these phenomena are presented below.

7.5.1. A building compliant with the actual technical requirements vs. a building with an increased standard of the insulation

Figure 7.3 shows the energy demand for heating and cooling of a single-family house with an area of 90 m^2 with natural ventilation for two external partition insulation scenarios according to the Polish technical requirements [57] (std) and passive building standard [58] (pass) and two weather data scenarios (current and future).

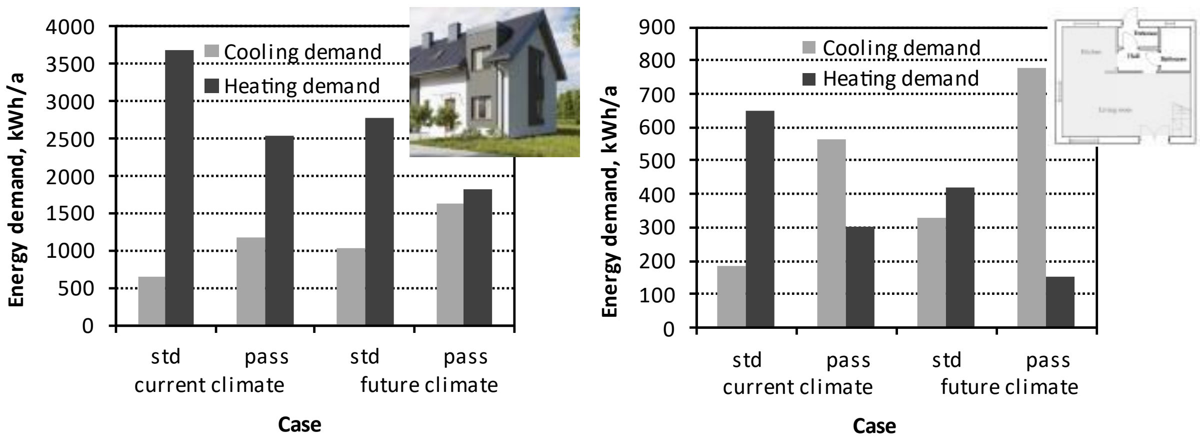

Fig. 7.3. The annual cooling and heating demand: the entire building (on the left) and the living room (on the right) [59]

Rys. 7.3. Roczne zapotrzebowanie na chłód i ogrzewanie: cały budynek (po lewej) i pokój dzienny (po prawej) [59]

Under current climatic conditions, the heat demand for the entire building is much higher than the cooling demand (about six times). In the case of using better insulation of the external partitions, a reduction in heat demand is observed (by approximately 31%). However, on the other hand, the value of cooling demand increases (by approximately 84%), especially in the living room with the highest internal heat gains (by approximately 212%). In the first case, the cooling demand accounts for only 17% of the heating demand, while in the second, it can be up to 46%. Currently, the Polish guidelines on the insulation of the external partitions are aimed at reducing the heating demand. However, as this study shows, in the era of a warming climate, cooling can have a significant share in the energy demand of the building. In this case, increasing the insulation of the external partitions has an adverse effect. The building becomes like a thermos and on hot days it cools down much slower. This problem intensifies in the case of rooms with large internal heat gains. Details of this study can be found in [59].

7.5.2. A brick building vs. a wooden building

Figures 7.4 and 7.5 show the energy consumption for heating and the global warming potential (GWP) index (greenhouse gases emission GHG) for a single-family house with an area of 150 m^2 with natural ventilation in various construction standards and for various heat sources. A brick building (B) and a wooden building (W) are considered for two scenarios of the external partition insulation according to the Polish technical requirements [57] (std) and the passive building standard [58] (pass). GWP calculations assume a 25-year lifetime of a building equipped with four different heat sources. For simplicity, the electricity necessary to heat pump is entirely generated by photovoltaic panels. Figure 7.6 shows the variability of indoor temperature in the living room and the total number of hours of thermal discomfort as a sum of all rooms throughout the year. All calculations were made for the current standard climate.

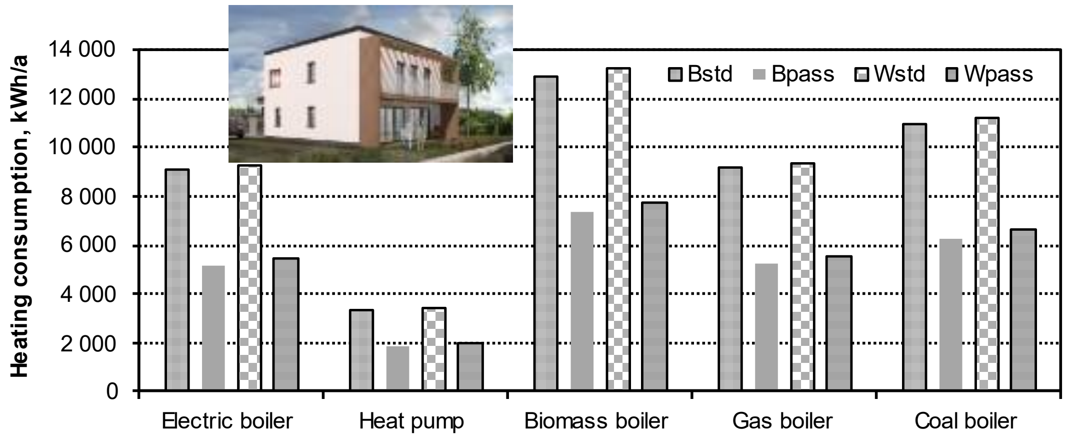

Fig. 7.4. The annual heating consumption depending on the type of building and heat source
Rys. 7.4. Roczne zużycie ciepła w zależności od rodzaju budynku i źródła ciepła

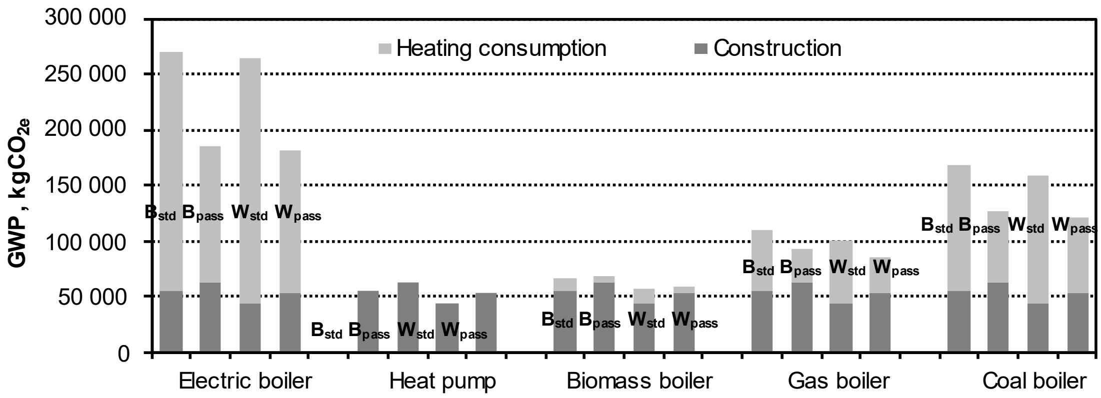

Fig. 7.5. Greenhouse gases emission related to building construction and energy consumption for heating, depending on the type of boiler and building (25 years of operation)

Rys. 7.5. Emisja gazów cieplarnianych związanych z konstrukcją budynku i zużyciem energii na ogrzewanie w zależności od typu kotła i budynku (25 lat eksploatacji)

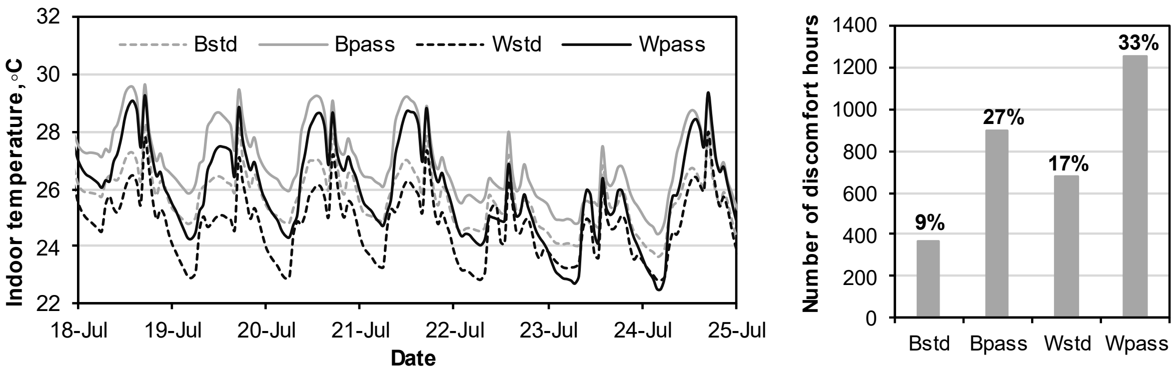

Fig. 7.6. Indoor temperature in the living room (on the left) and sum of discomfort hours for the entire building (on the right) depending on the type of building

Rys. 7.6. Temperatura wewnętrzna w salonie (po lewej) i suma godzin dyskomfortu dla całego budynku (po prawej) w zależności od typu budynku

Regardless of the case, for each building, the largest GHG emissions occur when an electric boiler is used. This is due to the fact that most of the electricity produced in Poland is generated as a result of burning coal in power plants. Due to the lower GHG emissions, houses made using the wood technology can be considered more attractive. Unfortunately, wooden buildings are worse than brick buildings in terms of thermal comfort, as there is a greater number of hours of thermal discomfort (up to twice the number of hours). When a building is very well insulated, it should be noted that it will be difficult to maintain a comfortable temperature in the summer without the use of air conditioning. In this study, on average, for 27% of the occupancy time for the B_{pass} building and even 33% of the occupancy time for the W_{pass} building, the rooms are too warm in the summer.

The most environmentally friendly heat sources, from the point of view of GWP, are a heat pump and a biomass boiler. The GHG emissions in a building with these sources are on average about 3–4 times lower (depending on the degree of insulation of the external partitions) compared to a building with an electric boiler. Houses with a gas boiler emit about 1.5 times more GWP on average, compared to buildings with a heat pump. Details of this study can be found in [60].

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8. PROMISING ENERGY TECHNOLOGIES TOWARDS SUSTAINABLE FUTURE

8.1. Public perception of energy transformation in Poland

According to a survey by the Public Opinion Research Center (CBOS) [1], the demand to move away from coal and develop other ways of energy generation meets with a favourable public reception and finds acceptance in all socio-demographic groups included in the analyses, although significant changes can be seen over the past few years. The data are shown in Figure 8.1. In 2016, half of the respondents believed it was necessary to focus on developing renewable energy sources (RES). In contrast, only 31% of respondents now support investing primarily in RES (19 percentage points less than previously). Supporters of only non-renewable energy sources are still a significant minority (8% vs. 5% in 2016). Still, there has been an increase in those who want to develop energy generation from renewable and non-renewable sources (up from 39% to 56%). Such a significant increase in support for a diversified energy mix should be attributed primarily to a jump in support for the development of nuclear energy [2, 3], which is mainly due to the instability of the geopolitical situation and the ongoing war in Ukraine, as well as the ambivalent attitude to the European climate policy of part of the population. An increase in support for the development of nuclear energy is declared by 76% of respondents, an increase of 32 percentage points over the year. The statistical results are shown in Figure 8.2.

The report [4] presents a study by the IBRiS studio on analysing the Polish society's opinion on renewable energy. Results are presented in Figure 8.3. The opinion of the respondents should be considered positive. The vast majority of respondents expect measurable benefits for the population and think the renewables to be the most modern and forward-looking, as well as security providing, type of energy.

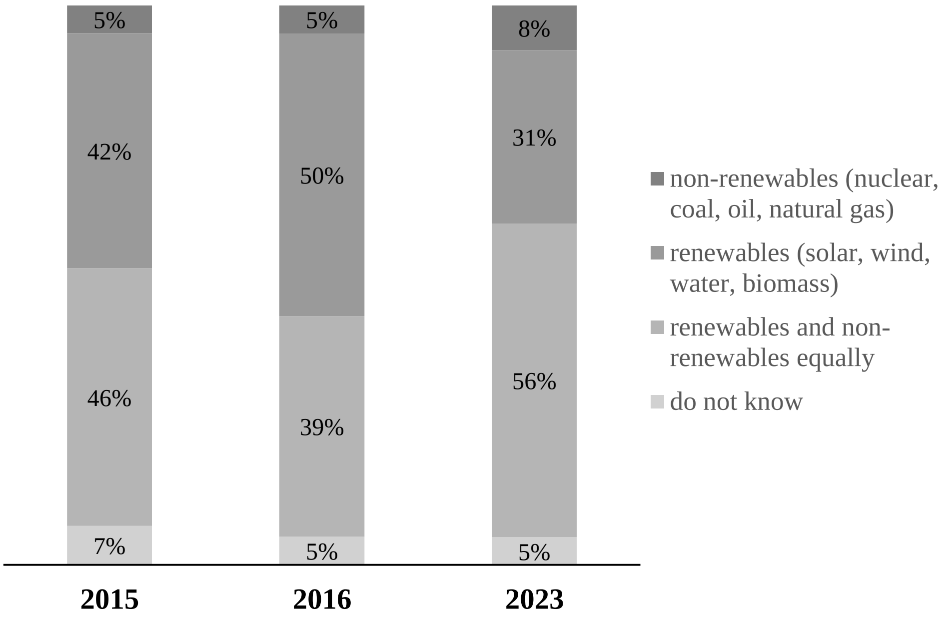

Fig. 8.1. Responses to the question about the energy area to focus on, based on the statistical study by CBOS [1]
Rys. 8.1. Odpowiedzi wskazujące obszar energetyki, na którego rozwoju należy się skoncentrować, na podstawie badań statystycznych CBOS [1]

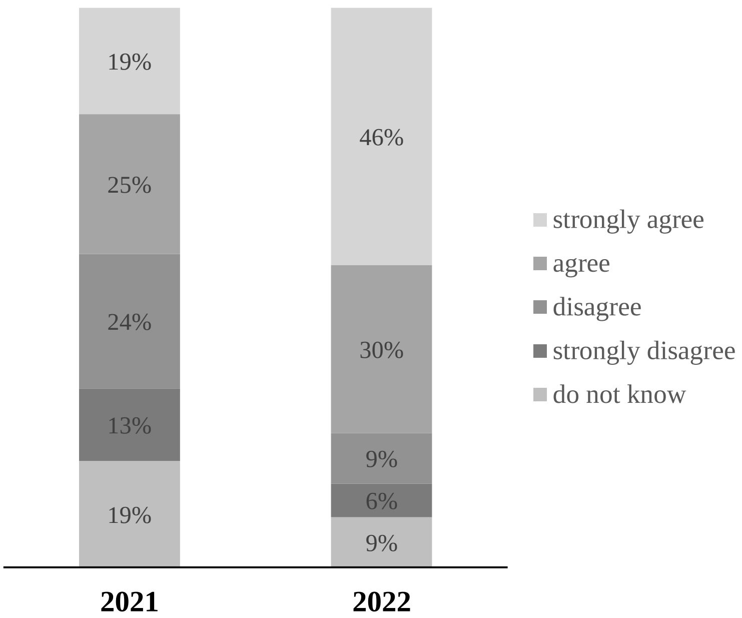

Fig. 8.2. Responses to the question whether you agree with the statement that the development of nuclear power in Poland is necessary if we want to move away from coal-based energy, based on the statistical study by CBOS [2]
Rys. 8.2. Odpowiedzi na pytanie dotyczące zgody ze stwierdzeniem, że rozwój energetyki jądrowej w Polsce jest konieczny, jeśli chcemy odchodzić od energetyki opartej na węglu, na podstawie badań statystycznych CBOS [2]

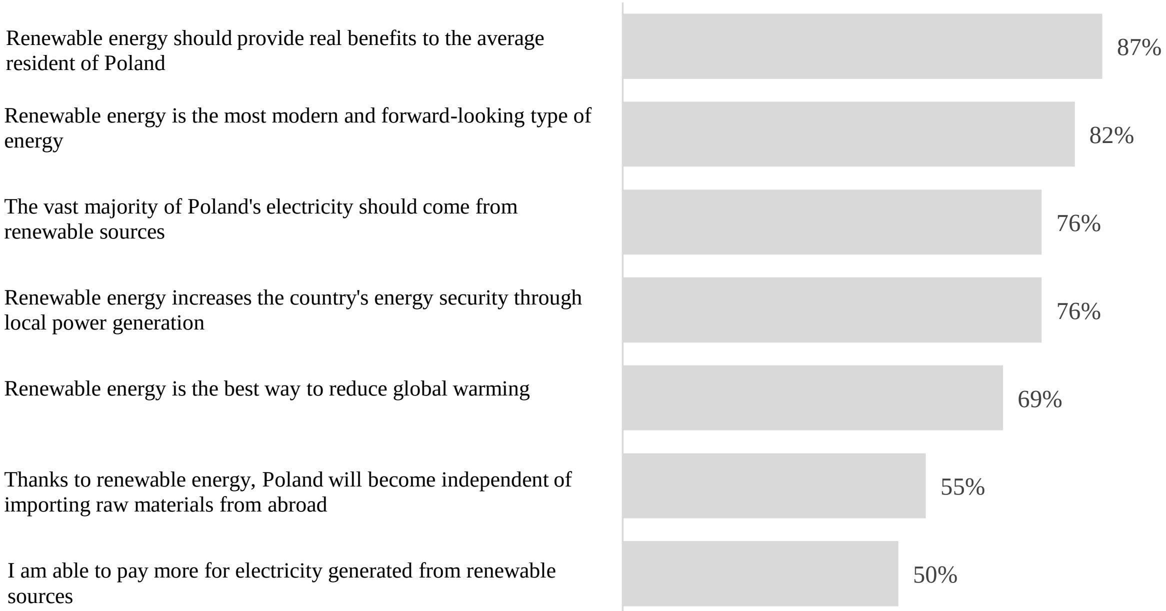

Fig. 8.3. Percentage of people supporting given statements regarding renewable energy sources, adapted from [4]
Rys. 8.3. Procent badanych zgadzających się z wybranymi opiniami o odnawialnych źródłach energii, na podstawie [4]

All public opinion polls on the subject under discussion tie together. The results of another survey by the CBOS studio [5], this time on wind energy, are shown in Fig. 8.4. Vast majority of Poles support the construction of wind farms on land, even taking into account smaller distances from buildings than possible under the current legislation.

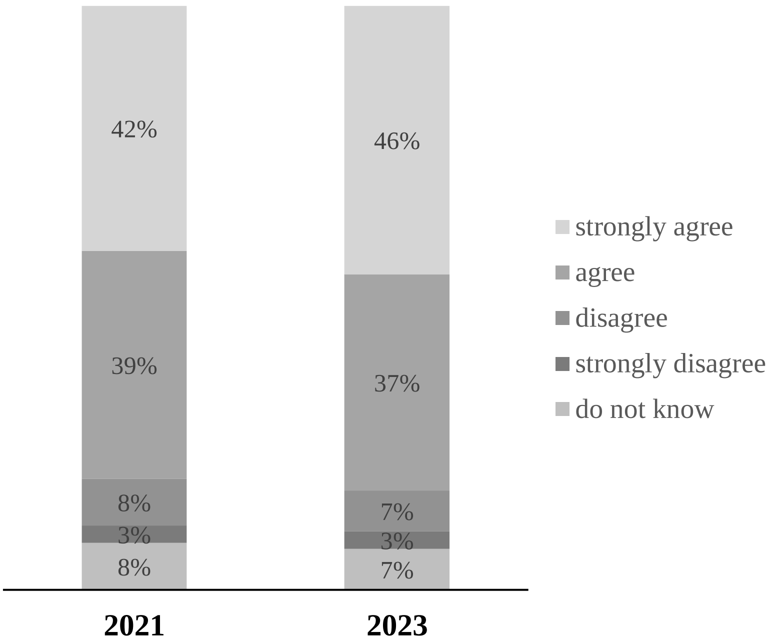

Fig. 8.4. Responses to the question regarding support for the development of onshore wind farms in Poland; based on the statistical study by CBOS, adapted from [5]
Rys. 8.4. Odpowiedzi na pytanie dotyczące poparcia rozwoju farm wiatrowych w Polsce, na podstawie badań statystycznych CBOS [5]

The briefly presented results of the public opinion analysis indicate that the vast majority of the public is aware of the need for an energy transition. The CBOS report [1] also demonstrates that most people expect renewables, which will generate the majority of electricity after 2050, to play a major role in ensuring climate neutrality.

The use of renewables, widely promoted in the EU for years, is a forward-looking way to produce energy. Still, it poses significant challenges, which include, first and foremost, the high investment cost and intermittent nature of production. Therefore, for renewable energy to become a reliable source of energy, in addition to the need for continually progressive reductions in expenditures, it is necessary to develop energy storage techniques that will allow the balancing of daily and seasonal loads resulting from fluctuating demand.

8.2. Large-scale system perspective

8.2.1. Hydrogen energy

Hydrogen is a chemical energy carrier with technically diverse production, storage, distribution and end-use methods. It is used in power generation, transportation, as well as in the chemical industry. From the point of view of the future application, it is mandatory to develop sustainable and environmentally friendly methods of producing this gas. As indicated by the authors of a monumental hydrogen has a potential as a fundamental component of the idea of a paradigm shift in the energy sector to one based on clean sources [6]. Although several decades have passed since the conception of the “hydrogen economy”, it is only in recent years that the hydrogen value chain has shown commercial justification for applications outside the chemical industry for general energy purposes. The significant decrease in the cost of solar and wind technologies and the steady improvement in the economic viability of investments in hydrogen technologies and side infrastructure are among the factors that make it possible [6].

In its 2022 Global Hydrogen Review report [7], the International Energy Agency identifies vital policy recommendations that can accelerate the development of low-carbon hydrogen generation and consumption:

- move from announcements to policy recommendations;
- raise ambitions for demand creation in key applications;

- identify opportunities for hydrogen infrastructure and ensure that short-term actions align with long-term plans;
- intensify international cooperation for hydrogen trade;
- remove regulatory barriers.

These actions are necessary because of the urgent need to accelerate the growth of global hydrogen demand. In 2021, hydrogen demand was 94 Mt, accounting for about 2.5% of global energy consumption. The IEA predicts that demand for this energy carrier could rise to 115 Mt in 2030, given the current government undertakings and emerging legislative frameworks (by September 2021, 26 countries had adopted national strategies for hydrogen energy development). To make the achievement of net zero-carbon in 2050 plausible, hydrogen use should already be at 200 Mt around 2030 [7]. The structure of future hydrogen use is indicated in Hydrogen Roadmap Europe [8]. This report forecasts the structure of hydrogen use in 2050. According to the ambitious scenario, the main actors in the total use of hydrogen will be transportation (30%) and heating and powering buildings (almost 26%). At the same time, the combined energy, storage and industrial power sectors will together account for 15.5% of total hydrogen use, as highlighted in [9].

Hydrogen production by water electrolysis is likely to become an economically competitive option shortly, primarily when the energy comes from renewable sources and is supported by policymakers through carbon tax measures and other additional financing mechanisms.

Green hydrogen generation

World has never been more committed to improving climate protection policies and decarbonizing economies [10]. Ongoing research into clean energy technologies will lead to technological breakthroughs and enable the introduction of socially acceptable technologies cost-effectively [11]. The most promising ideas currently being pursued focus on energy storage. The overall concept of energy storage is an integral part of the transformation of energy systems, burdened with many problems related to gas emissions that harm the health and have a significant negative impact on climate change [12]. Power-to-X (P2X) is a branch of technology in this area that brings the society a step closer to a fully energy-transformed economy. Green hydrogen can be considered a primary driver of this concept. A general conceptual diagram of an energy system operating based on hydrogen generation, storage and utilisation is shown in Figure 8.5.

The idea of P2X systems has gained a wide acceptance in the scientific community, as evidenced by the number of research projects currently underway worldwide [12].

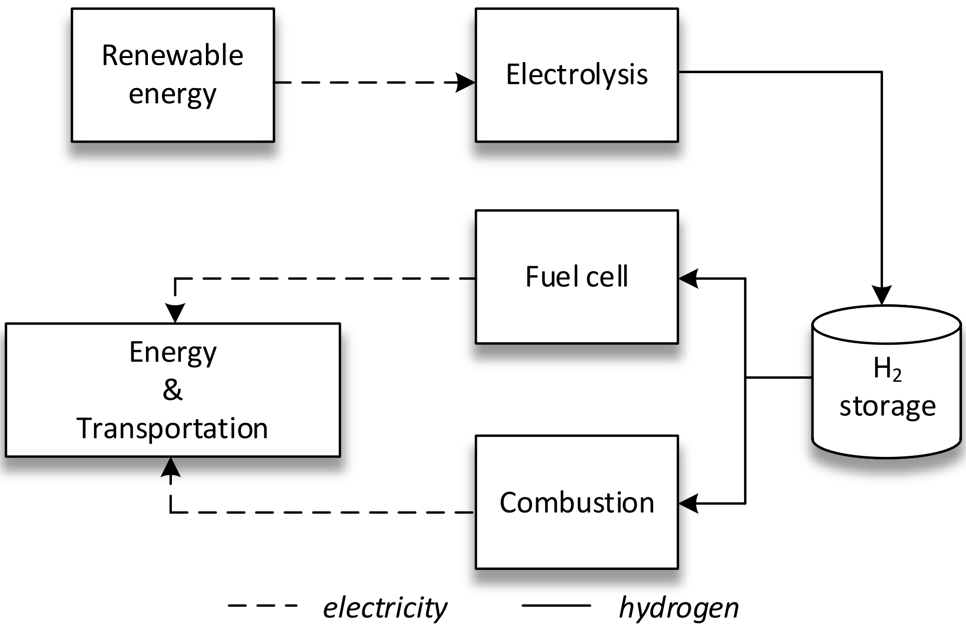

Fig. 8.5. Conceptual technology outline, adapted from [13]
Rys. 8.5. Koncepcja technologii, na podstawie [13]

The green hydrogen concept uses renewable energy sources to generate electricity and then converts it into hydrogen energy by electrolysing water in the H_2 generation plant. Since only water is used during the process, carbon dioxide emissions can be zero. Four basic electrolyser technologies are used to build hydrogen generators: solid oxide electrolysers (SOEC), alkaline electrolysers (ALK), proton exchange membrane electrolysers (PEM) and anion exchange membrane electrolysers (AEM). All of the technologies mentioned above are constantly under research. Still, two (ALK and PEM) can already be considered mature technologies with a high technology readiness level.

AEM electrolyser technology is relatively new in design compared to ALK and PEM electrolysers. Due to the use of new materials, AEM electrolysers can produce hydrogen with similar purity and pressure as ALK and PEM-type electrolysers while significantly reducing the corrosive effect of the electrolyte [14]. In the case of high-temperature solid oxide electrolysers, the operating medium is steam. The entire process takes place at temperatures up to 1000°C. The main advantage of high-temperature electrolysers is that they require less electricity than low-temperature electrolysers, which is due to the use of heat as the primary energy source necessary for the reaction to take place. As a result, much higher efficiency can be achieved, up to 90% [14]. The basic parameters of the most commonly used electrolysers are indicated in Table 8.1.

Table 8.1

Alkaline and PEM electrolysers parameters; adapted from [15]

Electrolyser type	Alkaline	PEM
Technology state	Mature	Mature
Load carrier	OH-	H+
Cathode material	Nickel	Platinum
Anode material	Nickel, Cobalt, Iron	Iridium, Ruthenium
Minimum operating temperature	20°C	20°C
Maximum operating temperature	120°C	80 (90)°C
Electrolyte	KOH or NaOH solution	Solid PFSA acid polymer
Theoretical pressure range	0.1–20 MPa	0.1–35 MPa
Current density	0.2–0.6 A/cm^2	0.6–3 A/cm^2
Electrolyser cell voltage	1.8–2.4 V	1.7–2.4 V
Possible of cyclic supply	Average	Good
Electrolyser lifetime	Under 100,000 h	10,000–50,000 h
Electrolyser energy consumption	4.2–5.9 kWh/Nm^3 H_2	4.1–5.6 kWh/Nm^3 H_2
Electrolyser efficiency	47–82%	62–90%
Water conductivity	Under 5 μS/cm	Under 1 μS/cm
Hydrogen purity	99.9%	99.999%

Green hydrogen costs

A key determinant for environmentally-friendly hydrogen generation technology is cost – both the investment and operating costs of such a project, as reflected in the levelized cost of hydrogen. Technical and economic analyses are widely described in the literature. An up-to-date review of ongoing research into the economic viability of investing in hydrogen systems is included in many publications [6, 15–17]. To date, the most favourable price is steam methane reforming. Nevertheless, a progressive reduction in the cost of green hydrogen can be seen, which is a good prognosis for the future. Current economic studies are presented in [9], from where Figure 8.6. is taken. It shows a levelized cost of hydrogen analysis for various operating parameters for two key hydrogen generation technologies (ALK electrolysers and PEM) based on energy from an integrated solar-wind farm. An analysis of the results presented in Figure 8.6. shows that, in general, for the analysed hydrogen output, alkaline generators are characterised by a favourable cost of hydrogen. PEM-type devices achieve significantly worse results regarding the economic effect of the plant operation. Moreover, the alkaline generator is more resilient in varying economic conditions [9].

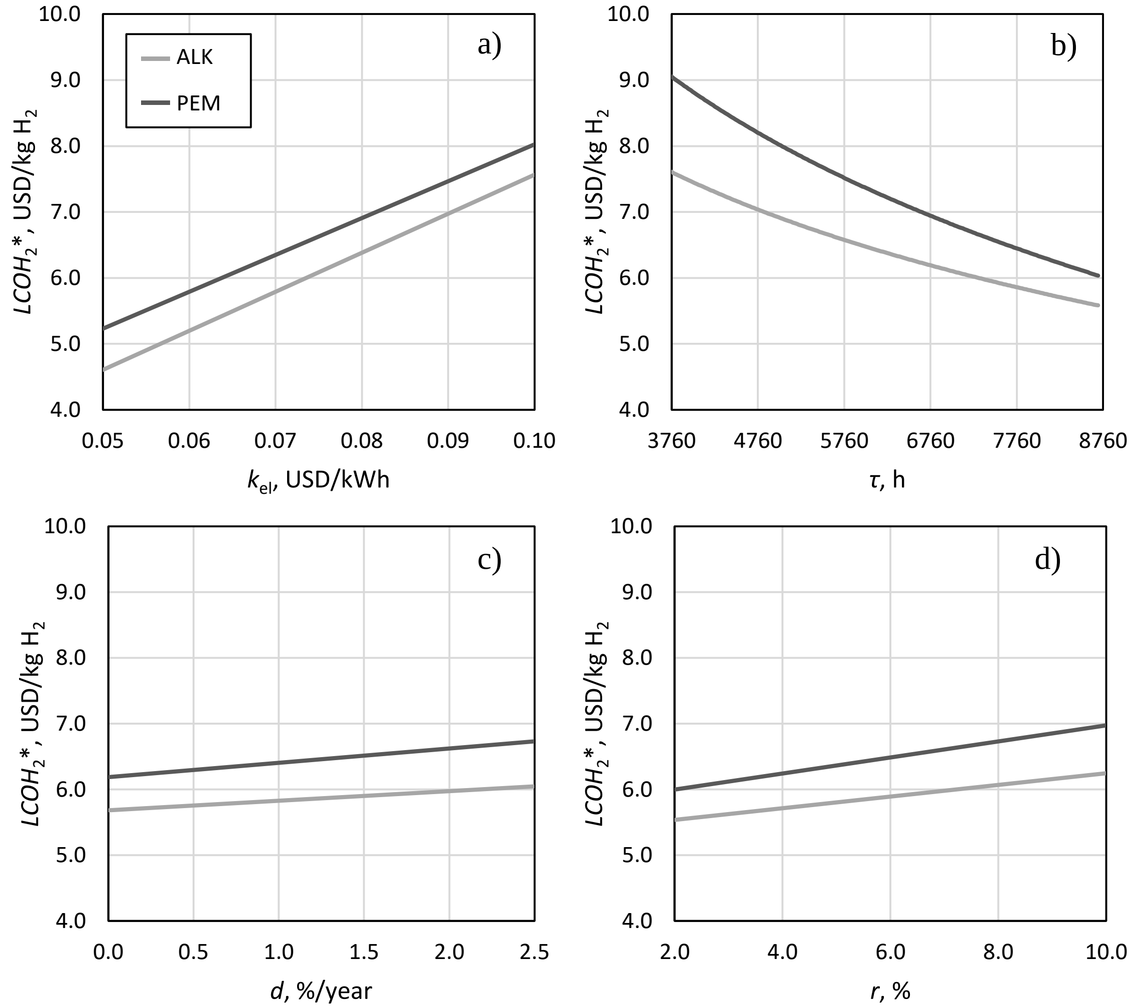

Fig. 8.6. Results of the analysis of the levelised cost of hydrogen with respect to various operating parameters in alkaline and PEM-based hydrogen generators, adapted from [9]
Rys. 8.6. Rezultaty analizy uśrednionego kosztu wytwarzania wodoru w generatorach AEM oraz PEM w funkcji wybranych parametrów, na podstawie [9]

8.2.2. Other selected technologies for energy storage

The need to increase the scope of the regulation of the power put into the power system from large centralised sources as a consequence of the growing share of renewables in the energy mix is also favouring other energy storage technologies. Techniques with a significant potential include compressed air energy storage [18]. In this system, accumulation is realised by transforming electrical energy into the potential energy of compressed gas. Atmospheric air is directed to the reservoir through the compressor. Reversing the direction of energy transformation requires using an expander [19]. The feature distinguishing CAES from other energy storage technologies at this stage of technological development is the potential for use within the large-scale industry due to the technical and economic viability of building high-capacity systems.

The ability to achieve power outputs of several hundred megawatts makes CAES competitive with pumped hydropower plants, which have been known for years.

Similarly, the CAES systems allow long discharge periods, even dozens of hours. A debatable issue is the amount of capital expenditure of the described technology, which strongly depends on the location. The high technological maturity resulting from the maturity of the commercially used components in these installations makes it possible to reduce the unit investment costs of the machinery. These types of components function on a daily basis within well-known power systems or in the chemical industry. On the other hand, the cost of the air reservoir, which depends on geological conditions, should be considered a critical factor. Most often, salt caverns, which are formations created by the exploitation of rock salt deposits, are considered air reservoirs. The prevailing conditions are advantageous for maintaining a stable pressure level of the stored air. In addition, the following should be considered alternative sites: porous layers of partially exploited natural gas deposits; water-bearing layers; decommissioned mines; rock caverns [20, 21].

Pumped-Hydro Storage (PHS) power plants are most commonly used to stabilise the operation of the power grid. PHS power plants convert electrical energy into the potential energy of water. In this form, the energy can be stored and converted back into electricity. PHS power plants have a high efficiency of 70–85% [15]. However, the possibilities of using these plants are limited. This is due to the need to choose an appropriate geographic location. Also required are the availability of significant water resources and an adequate height difference between the lower and upper reservoirs of the power plant. In addition, installations of this type require a large area, and their construction significantly interferes with the natural environment, resulting in local disputes over the location of PHS.

Some of the most promising energy storage methods also include storage in the form of synthetic fuels such as methane, methanol, and dimethyl ether. The products obtained from chemical syntheses can be used in the energy industry as fuels (in the case of an increased demand), but also in transportation, industry or as a chemical feedstock for further syntheses. The carbon required for fuel synthesis can come, for example, from carbon dioxide captured from the existing conventional power plants, so the fuel production process will positively impact reducing the anthropogenic CO_2 emissions. However, unlike the carbon capture and storage (CCS) technology, technical problems and risks regarding long-term carbon storage will be avoided. Using this method of CO_2 utilisation instead of geological storage combined with the use of green hydrogen can lead to an environmentally-beneficial fuel cycle based on the sustainable production of synthetic fuels that can stabilise the electricity system [22]. Methanol seems to be a particularly interesting medium; it is discussed as a liquid energy carrier because it is already produced from hydrogen and carbon dioxide at a high technological readiness level (TRL). An ideal schematic of a methanol generation system is shown in Figure 8.7. Methanol is more straightforward to operate, store and transport than methane. In addition, unlike hydrogen, it is a liquid under normal conditions. It does not require high pressures or low temperatures, and its energy density by volume is higher. Current crude oil ships could be used to transport methanol with minor modifications. Methanol can be used in the transportation and chemical sectors [23].

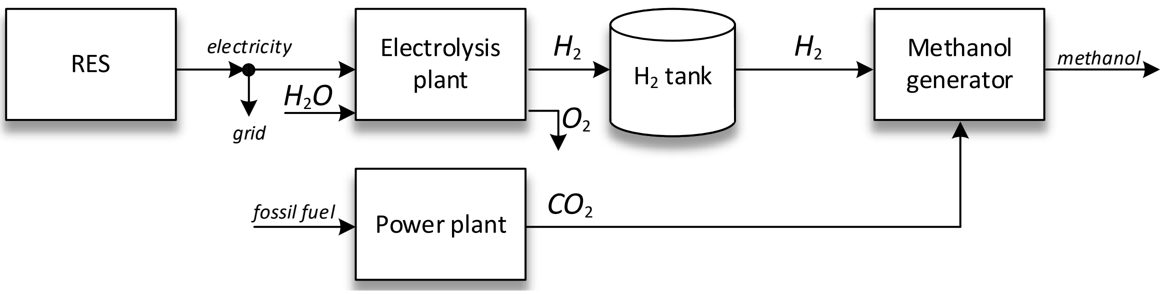

Fig. 8.7. Simplified scheme of power-to-methanol technology, adapted from [12]
Rys. 8.7. Uproszczony schemat technologii power-to-methanol, na podstawie [12]

8.2.3. Recent studies in large-scale energy storage systems

Large-scale energy storage systems are dedicated to operating in the regime of daily price arbitrage, mainly because of the need to increase the flexibility of the power system under the influence of the intensive development of renewable energy sources. Due to their relatively high capacities, they can perform several auxiliary functions in the power system, such as black-start or participation in the balancing market for grid parameters. Decarbonising the energy sector also includes studying new or expanded energy storage system concepts. The concept of an adiabatic CAES involves eliminating the combustion process of an auxiliary fuel (usually natural gas) from the system cycle to heat the expanded air [18]. The combustion process is replaced by the development of a Thermal Energy Storage (TES) tank, which captures and stores the heat of gas compression at the charging stage and transfers it to regenerated air at the discharging phase. The energy efficiency of the proposed systems, depending on the configuration, ranges from 65% to 70%. The patented invention of the Silesian University of Technology researchers is a system for storing compressed gas and constructing a TES tank in a post-mining shaft [24]. The deep shafts in Poland, which are up to 1,000 meters deep, ensure about 60,000 m^3 of compressed air reservoir volume, which is lower compared to installations based on salt caverns [25]. On the other hand, due to the multitude of coal mine shafts in Poland, especially in the Upper Silesia area, it is possible to intensively expand the network of energy storage facilities, which can independently be subjected to the disposition of the power grid operator. Using a post-mining shaft minimises the risk of fire compared to storing compressed gas in mine tunnels due to the non-contact with coal residues and protection against the diffusion of underground ignitable gases. In addition, the mine shaft structure is geologically stable and protected by a casing, which, however, requires additional surface protection to limit the permeability of the gas to the rock mass. Locating the heat storage tank inside the shaft ensures that the heat storage system is isolated from the changing ambient conditions, significantly reducing heat loss to the environment and providing stability for this component regardless of the season. Moreover, the support of the storage tank's design allows the transfer of stresses resulting from differential pressure to the concrete casing, which enables the construction of a thin-walled tank. This significantly reduces the cost of the system compared to the adiabatic CAES systems, where the TES had to be an above-ground structure. Installation of the heat storage tank in the mine shaft volume determines the TES tank's maximum diameter limited by the inside diameter of the shaft casing [26]. This leads to the requirement for an exceptionally slender tank relative to the previously proposed [27–29]. Through an experimental-numerical analysis including both studies of the thermophysical parameters of the rock material and heat transfer between air and basalt, it has been proven that heat storage in porous rock material is reasonable from the perspective of maintaining relatively high efficiency of heat management processes [30]. The round-trip energy efficiency of the lab-scale tank ranged from 91% to 93%, depending on the mass flow rate of the heat-transfer fluid. It was also proved that the increased slenderness of the heat storage tank positively preserves the potential of the stored energy [31]. The exergy efficiency of the slender storage tank, which height-to-diameter ratio corresponds to the case of a full-scale system built in a post-mining shaft, was 69%. In contrast, the geometry corresponding to the above-ground heat accumulators provides a cycle exergy efficiency of 56%. It was also shown that the value of energy and exergy efficiency strongly depends on the parameters characterizing the heat accumulator – including the rock material's diameter or the rock bed's porosity.

The invention patented by the Silesian University of Technology researchers is also a hybrid energy storage system that comprises a subsystem for CO_2 compression, hydrogen and synthetic natural gas generation [32]. The closed-cycle CO_2 compression and storage system's operation was scheduled for the electricity price valley period. Storage of supercritical CO_2 in isobaric high- and low-pressure tanks provides for volume reduction [33]. The hydrogen generation section is intended to integrate renewable energy sources with the hydrogen to be used in the production of synthetic natural gas in the Sabatier reaction, which supplements carbon dioxide extracted from a low-pressure reservoir [34]. The system chain closes with a synthetic natural gas combustion subsystem in an oxygen atmosphere, which operates during electricity demand periods. The exhaust gas is directed to an expander and, after drying, to a low-pressure CO_2 tank.

8.3. Prosumer perspective

The demand for urgent investment in effective and competitive power grid solutions based on decentralised sources, including primarily renewables and microgeneration (μCHP) systems, are highlighted regarding the energy infrastructure priorities. The μCHP systems can provide a countermeasure to reduce the load on the centralised energy systems while enabling the active participation of end users in energy management. Reducing emissions can be achieved using lower-emission or renewable sources in households. Increasing the share of renewable and distributed energy sources in the generation structure will increase the interest in such technologies on the community level. Achieving the regulatory required shares of renewable energy in the total production and reducing emissions will be achieved through installing new, upgrading current technological assets, and supporting decentralised energy generation.

As described in paper [35], the term "prosumer" was introduced in 1980 and was unrelated to energy. Two words, "producer" and "consumer", were merged to characterize the changing perspective in the post-industrial era. The term is very meaningful and interesting. It has taken hold in various areas, including the energy sector. However, it has been described differently in this field as well; for example, the basic understanding is that a prosumer is a user who "(...) not only consumes energy, but also produces it" [36]; a prosumer can also sell energy (while connected to the grid) [37], and even store or transport electricity [38]. According to [39], a prosumer can also actively participate in the primary goal (energy savings) by buying and selling energy online. In Poland, the legal definition of a prosumer is provided by the Law on Renewable Energy Sources (RES) [40], and it limits energy generation to renewable sources [35].

In order to stimulate the development of legislative support for distributed energy, a draft “Strategy for the Development of Distributed Energy in Poland until 2040” was created and published in January 2023 [41]. According to the authors, the document proposes necessary measures in this area of energy to support the national energy strategy. Firstly, the comprehensive collection of materials on the legal aspects of the distributed sources in Poland should be appreciated. As highlighted in the document, the national legislation does not contain a definition of distributed generation, so a proposal: “Distributed energy is energy generation sources and energy storage intended for local use, connected directly or indirectly (using household installations, industrial networks, etc.) to the distribution system” has been presented to make the term more precise [41].

The newly proposed definition of the distributed generation lines up with the general concept for prosumer generation considered in the scientific literature. The following section describes recent advances in terms of increasing self-sufficiency and cost-effectiveness of the distributed energy solutions dedicated to households or prosumers’ federations, sometimes called sustainable energy clusters.

8.3.1. Prosumer self-sufficiency

Prosumer independence in terms of energy supply is a particularly tricky issue regarding the variability of energy consumption in individual buildings. The trends are visible when large groups of energy users are considered. Nevertheless, considering individual cases still poses a research challenge in terms of concept and technical implementation. Some solutions are successfully applied in the context of off-grid units; however, prosumers cooperating with the distribution grid prevail in wide implementation of prosumer concepts. This statement is supported by the results of a German study, which indicated that leaving the grid is not yet economically feasible for a prosumer, even in a favourable location in terms of weather conditions [42]. Such prosumers will encounter substantial technical and economic problems, e.g., large amounts of excess energy in the summer or high investment costs for a high-capacity battery system.

As paper [35] indicates, energy self-sufficiency can be pursued through various means. In this case, the prosumer relied on gas-fired microgeneration, supplementing its electricity needs with photovoltaics. However, the level of self-sufficiency increased significantly with the use of a small electricity storage tank, which allowed for the time coordination of electricity generation and consumption. Despite being flexible and providing a high level of power security, the solutions proposed here are burdened with the negative aspects of using the natural gas. Full electrification is being considered the next step towards future fully-sustainable systems. Therefore, cases of prosumers based only on renewable sources are considered in the literature.

An interesting perspective on the electrification of prosumer systems is shown in paper [43]. The authors explore the potential for prosumer self-sufficiency with stationary battery systems, but also with a fleet of electric cars and neighbourhood level coordination of energy sharing. While calculations indicate that with the proper internal billing mechanism, this solution can be economically competitive with prosumers, the high importance of the accuracy of energy consumption and generation predictions is pointed out. Electric cars are also considered a way to increase prosumer self-sufficiency in paper [44]. The authors analysed several variants of energy consumption profiles. They assessed the impact of individual charger parameters on prosumer energy-supply stability. Particularly interesting conclusions include the negligible impact of using a bidirectional charger instead of a unidirectional one. However, it should be noted that the considered work grid feed-in for the EV was not allowed within the operation strategy. The primary mechanism shaping the prosumer here was the timing of connecting the vehicle for charging. Nevertheless, with the right operation strategy, the use of the EV can lead to an increase in self-sufficiency and an improvement in the lifetime of the battery used in the vehicle. In paper [45], a novel dynamic pricing model for a microgrid of prosumers was presented. The participants of the microgrid rely on the photovoltaic installations. The general concept of a microgrid cooperating with the utility grid seems reasonable, especially if the dynamic penalties mechanism and forecasting of load profiles would be included. Microgrid operator could be aiming at optimisation of energy consumption, reducing transmission losses and minimising the environmental impact of the energy generation.

The consumer perspective on energy generation and management is still under development. The previously signalled issues related to the technical implementation of the concept of sustainable development in the aspect of small-scale energy are the seeds of problems that will still be faced. Environmental [46] or economic [47] factors of the implementation of prosumerism are constantly being analysed. Nevertheless, a society aware of the need for a change in order to enable the coming transformation is ready to face these challenges.

8.3.2. Energy storage for prosumers

Electricity storage units are one of the critical elements in the development of small-scale distributed energy technologies. They make it possible to temporarily, mainly on a daily cycle, balance the energy produced from sources with intermittent production, such as photovoltaic panels or a micro-cogeneration system that also works for thermal needs. Lithium batteries are the dominant technology in the field of small-scale storage for domestic use. Within the broad concept of the lithium-ion battery, several technologies are distinguished, characterised by different positive electrode (cathode) materials. Batteries available on the market belong to the following groups:

- Lithium iron phosphate ($LiFePO_4$) – market designation LFP,
- Lithium nickel manganese cobalt ($LiNixMnyCozO_2$) – market designation NMC,
- Lithium nickel cobalt aluminium oxides ($LiNiCoAlO_2$) – market designation NCA.

The collected data are shown in Figure 8.8. with the manufacturing technology. The data show that manganese (NMC) storage batteries have the highest stored energy density. The charging cycle of a battery is usually defined as one full charge and one discharge. For LFP and NCA technologies, a higher number of possible cycles is generally indicated. For NMC technology, a lower lifetime is indicated [48].

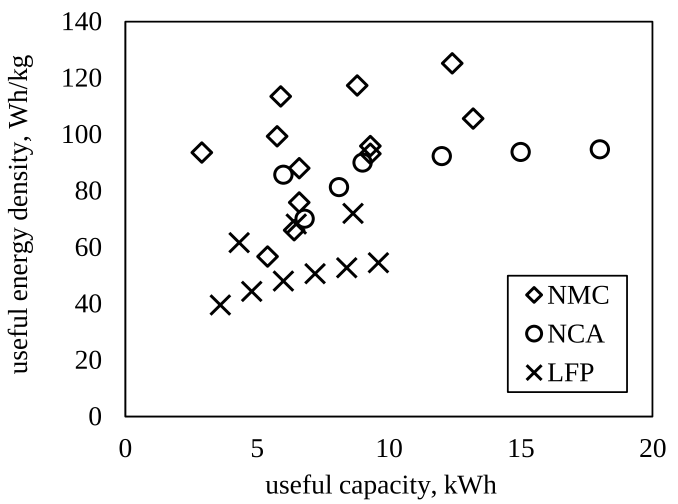

Fig. 8.8. Exemplary parameters of residential electrical energy storage, adapted from [48]
Rys. 8.8. Przykładowe parametry domowych zasobników energii elektrycznej, na podstawie [48]

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LIST OF TABLES AND FIGURES

SPIS RYSUNKÓW

SUSTAINABLE PRODUCTION AND CONSUMPTION

SELECTED ENVIRONMENTAL ASPECTS

Abstract

The monograph presents selected problems concerning sustainable production and consumption in terms of environmental aspects.

Chapter 2 is dedicated to the sustainable soil management. It presents an approach based on the sustainable use of soil resources ensuring a balance between environmental protection, use and productivity of soils. The EU 2030 Strategy aims to remediate all soils in Europe by 2050, increase their resilience and ensure their adequate protection. Soil management fits into eight of the 17 Sustainable Development Goals. Experts from institutes supervised by the Minister of Agriculture and Rural Development have developed a lot of practices that can be applied in Polish agriculture with a view of a sustainable soil management in agriculture, compiled in the form of a Polish Code of Good Agricultural Practice. “Soil geography” has been presented as a scientific discipline which makes it possible to understand the links between soil science and other sciences in order to realise certain objectives of a sustainable soil development without losing soil functionality. Spreading awareness of sustainable soil management practices is one of the key factors for climate change adaptation, not only in agriculture. The development of systemic, optimised and locally adapted solutions should involve all soil users. This means going beyond the traditional agronomic and economic knowledge schemes. It points to the need to analyse the interactions between soil, water, atmosphere, biodiversity and landscape.

Chapter 3 describes the ever-increasing problem of the lack of availability of water of adequate quality, which is a key element of almost all branches of the industry. The classification of the most common pollutants in the aquatic environment was also presented, with a particular emphasis on organic micropollutants and microplastics. In addition, the possibilities of predicting the phenomenon of water shortage as well as

methods of counteracting it through the proper management of available water resources based on the assumptions of the circular economy were indicated.

Chapter 4 of the book delves into the advanced technologies and methods used in municipal wastewater treatment. A particular focus is put on addressing the problem of excess nutrients entering the environment, which leads to harmful eutrophication. The chapter provides detailed explanations of the processes and technologies employed to effectively remove nitrogen and phosphorus from wastewater. Additionally, it highlights the emerging trend of recovering valuable nutrients from wastewater. The presence of micropollutants in wastewater is also briefly described. The final section focuses on the current trends towards the energy self-sufficiency of wastewater treatment plants and introduces the concept of transforming these plants into biorefineries, where valuable resources are recovered and utilised.

Chapter 5 is dedicated to the sustainable waste economy. It presents the problem of waste in the context of the present and future waste management hierarchy, which is based on the Zero Waste principle. The chapter deals with three main aspects of waste management in the context of Sustainable Development Goals (SDG): rational waste management, responsible consumption and sustainable production. Then, the article discusses three tendencies which shape waste management and presents statistical data concerning waste production in Europe and in the world and the methods of their management. Subsequently, philosophies were presented that allow reducing consumerism and turning radically or gradually to Zero Waste or Less Waste styles. Issues related to ecological education of the present and future generations were also raised. The chapter describes aspects related to companies' incorporation of new business models based on the circular economy which provide opportunities to eliminate waste. The discussed solution allows us to perceive waste as resources. The chapter presents examples of various activities undertaken by companies which successfully implement the circular economy.

Chapter 6 discusses the issue of atmospheric air quality, which is crucial in terms of sustainable development. Special notice is paid to the health risks and a negative impact on the public health associated with air pollution. More attention is drawn to the mortality rate due to poor air quality in countries with a varying wealth level. Sources of air emissions of hazardous substances and trends in pollutant emissions variability over the last 15 years in EU countries are indicated. Air quality recommendations prepared by the World Health Organization (WHO) are discussed and compared with standards applicable in EU and non-EU countries. The problem of greenhouse gas emissions with its impact on climate change, and also general challenges and opportunities connected with improving air quality, are also presented.

Chapter 7 is dedicated to the issues of the indoor environment and sustainable buildings. In the first section, the concept of a green building is defined and its features are provided; the most important standards for the indoor environment quality and certificates providing the buildings with the title of a sustainable building are discussed. Furthermore, factors of the indoor environment quality are discussed, including thermal comfort and indoor air quality, and basic information on the methodology of environmental, economic and social assessment of buildings throughout their life cycle is provided. The advantages of this LCA methodology and its limitations are determined. The next section discusses the current standard of buildings in Poland in terms of the use of energy sources and the level of obtaining certificates of sustainable buildings. The chapter ends with the results of an exemplary research on the energy and environmental assessment of single-family houses in Poland.

Chapter 8 is devoted to novel energy generation technologies capable of contributing to the idea of sustainable development. The latest trends in energy systems research are indicated. The current level of public acceptance of the energy transition process and support for selected technologies is analysed. Both a system perspective, including green hydrogen and large-scale energy storage, and a local perspective, including the concept of prosumer energy self-sufficiency, is considered.

ZRÓWNOWAŻONA PRODUKCJA I KONSUMPCJA

WYBRANE ASPEKTY ŚRODOWISKOWE

Streszczenie

Monografia przedstawia wybrane problemy dotyczące zrównoważonej produkcji i konsumpcji w aspekcie środowiskowym.

Rozdział 2 poświęcono zrównoważonemu gospodarowaniu glebą. Przedstawiono podejście oparte na trwałym wykorzystaniu zasobów glebowych, zapewniające równowagę między ochroną środowiska naturalnego, użytkowaniem a produktywnością gleb. Strategia UE 2030 ma na celu rekultywację do 2050 r. wszystkich gleb w Europie, zwiększenie ich odporności i zapewnienie im odpowiedniej ochrony. Gospodarowanie glebą wpisuje się w 8 z 17 celów zrównoważonego rozwoju. Eksperci z instytutów nadzorowanych przez ministra rolnictwa i rozwoju wsi opracowali wiele możliwych do zastosowania w polskim rolnictwie praktyk mających na celu zrównoważone gospodarowanie gruntami w rolnictwie zebrane w postaci Kodeksu Dobrej Praktyki Rolnej. Wskazano „geografię gleb" jako dyscyplinę naukową, umożliwiającą poznanie powiazań pomiędzy gleboznawstwem i innymi naukami w celu realizacji określonych założeń zrównoważonego rozwoju gleb bez utraty ich funkcjonalności. Szerzenie wiedzy na temat praktyk zrównoważonego gospodarowania glebą jest jednym z kluczowych czynników adaptacji do zmian klimatu nie tylko w rolnictwie. W opracowaniu systemowych, zoptymalizowanych i lokalnie zaadaptowanych rozwiązań powinni uczestniczyć wszyscy użytkownicy gleb. Oznacza to wykraczanie poza tradycyjne schematy agronomicznej i ekonomicznej wiedzy. Wskazuje na potrzebę analizy interakcji pomiędzy glebą, wodą, atmosferą, bioróżnodnością i krajobrazem.

Rozdział 3 opisuje stale narastający problem braku dostępności wody o odpowiedniej jakości, która stanowi kluczowy element niemal wszystkich gałęzi przemysłu. Przedstawiona została również klasyfikacja zanieczyszczeń najczęściej spotykanych w środowisku wodnym ze szczególnym uwzględnieniem

mikrozanieczyszczeń organicznych i mikroplastiku. Wskazane zostały ponadto możliwości przewidywania zjawiska niedoboru wody oraz metody przeciwdziałania przez właściwe gospodarowanie dostępnymi zasobami wodnymi na podstawie założeń gospodarki o obiegu zamkniętym.

W rozdziale 4 opisano współczesne technologie i procesy związane z oczyszczaniem ścieków komunalnych. Zwrócono szczególną uwagę na problem z dopływem do środowiska substancji biogennych powodujących eutrofizację. Z tego względu szczegółowo zostały opisane procesy i technologie związane z usuwaniem azotu i fosforu. Wskazano także na obecną tendencję związaną z odzyskiem biogenów ze ścieków. Opisano też krótko problem mikrozanieczyszczeń występujących w ściekach. W ostatnim podrozdziale skupiono się na obecnych trendach związanych z samowystarczalnością energetyczną oczyszczalni, a także ze współczesną koncepcją oczyszczalni jako biorafinerii.

Rozdział 5 poświęcono zrównoważonej gospodarce odpadami. Przedstawiono w nim problematykę odpadów w kontekście obecnej oraz przyszłej hierarchii postępowania z nimi, która oparta jest na zasadzie Zero Waste. W rozdziale poruszono trzy główne aspekty związane z gospodarką odpadami w kontekście zrównoważonego rozwoju: racjonalna gospodarka odpadami, świadomy konsument i zrównoważona produkcja. Następnie omówiono trendy kształtujące gospodarkę odpadami, przedstawiono dane statystyczne dotyczące wytwarzania odpadów w Europie i na świecie oraz sposobów ich zagospodarowania. Opisano również filozofie, które pozwalają ograniczyć konsumpcjonizm i radykalnie lub stopniowo przejść na styl Zero Waste czy Less Waste. Poruszono również kwestię związaną z edukacją ekologiczną obecnych i przyszłych pokoleń. W rozdziale opisano aspekty dotyczące wdrażania przez firmy na całym świecie nowych modeli biznesowych opartych na gospodarce o obiegu zamkniętym, które stwarzają szanse na wyeliminowanie odpadów. Opisywane rozwiązanie umożliwia postrzeganie odpadów jako zasobów. W rozdziale przedstawiono przykłady różnych działalności, które w swoich przedsiębiorstwach wdrażają z sukcesem gospodarkę cyrkularną.

W rozdziale 6 omówiono zagadnienie jakości powietrza atmosferycznego, które ma kluczowe znaczenie w aspekcie zrównoważonego rozwoju. Szczególną uwagę poświęcono zagrożeniom zdrowotnym związanym z zanieczyszczeniami powietrza i ich negatywnemu wpływowi na zdrowie publiczne. Zwrócono uwagę na współczynniki umieralności z powodu złej jakości powietrza w krajach o różnym stopniu zamożności. Wskazano źródła emisji substancji niebezpiecznych do powietrza oraz trendy w emisjach zanieczyszczeń na przestrzeni ostatnich 15 lat w krajach UE.

Omówiono standardy jakości powietrza zalecane przez Światową Organizację Zdrowia (WHO), obowiązujące w krajach UE oraz w krajach spoza UE. Przedstawiono problem emisji gazów cieplarnianych, które mają znaczący wpływ na zmiany klimatyczne oraz możliwości poprawy jakości powietrza.

Rozdział 7 poświęcono zagadnieniom środowiska wewnętrznego i zrównoważonym budynkom. Na początku zdefiniowano pojęcie zielonego budynku i podano jego cechy, omówiono najważniejsze normy dotyczące jakości środowiska wewnętrznego i certyfikaty nadające budynkom standard budynku zrównoważonego. Dalej omówiono podstawowe wskaźniki jakości środowiska wewnętrznego, w tym komfort cieplny i jakość powietrza wewnętrznego, oraz podano podstawowe informacje dotyczące metodologii oceny środowiskowej, ekonomicznej i społecznej budynków w całym cyklu ich życia. Określono zalety metodologii LCA oraz jej ograniczenia. W kolejnej części tego rozdziału omówiono obecny standard budynków w Polsce pod względem wykorzystania źródeł energii oraz stopnia pozyskiwania certyfikatów zrównoważonego budownictwa. Rozdział kończą wyniki przykładowych badań dotyczących oceny energetycznej i środowiskowej domów jednorodzinnych w Polsce.

Rozdział 8 poświęcono innowacyjnym technologiom wytwarzania energii, które mają szansę przyczynić się do realizacji idei zrównoważonego rozwoju. Wskazano najnowsze trendy w badaniach systemów energetycznych. Przeanalizowano obecny poziom akceptacji społecznej dla procesu transformacji energetycznej oraz przychylność dla wybranych technologii. Rozważono perspektywę zarówno systemową, zawierającą m.in. zielony wodór oraz wielkoskalowe magazyny energii, jak i perspektywę lokalną, mieszczącą w sobie koncepcję samowystarczalności energetycznej prosumenta.

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