New Insights Into the Green Deal Strategies

Water, Raw Materials and Energy

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Introduction

In today's world, cooperation between various stakeholder groups is very important to achieve the intended goals. As part of the 3rd International Conference – Strategies toward Green Deal Implementation – Water, Raw Materials & Energy (ICGreenDeal 2022), three stakeholder groups – scientists, entrepreneurs and policy makers – gathered to create a platform for exchanging information on how to prevent the effects of ongoing climate change. The purpose of this event was to present the issue of climate change and ways to prevent it eg. innovative solutions (technological, environmental, economic, and social) that can be implemented under the Green Deal Strategies in the area of Water, Raw Materials and Energy.

The ICGreenDeal 2022 was organised for the third time by Division of Biogenic Raw Materials of the Mineral and Energy Economy Research Institute, Polish Academy of Sciences. It took place between 5 and 7th December 2022 as virtual event to ensure that all interested listeners and speakers around the world can participate. The conference program included a total of 15 panel sessions during which a total of 74 speeches 50 posters were presented.

This Monograph "New Insights Into the Green Deal Strategies" includes the selected papers that have been presented during the 3rd edition of International Conference on Strategies toward Green Deal Implementation – Water, Raw Materials & Energy. Many thanks for all Authors and Reviewers for their valuable work in the preparation of papers and their reviews.

Kind regards,
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Analysis of the proposal to adopt air quality standards in the EU in accordance with the WHO recommendations

Abstract: The problem of air pollution is a global challenge. In the EU, Poland is one of the top countries with the worst air quality. In response to the growing scale of the problem, on October 2022, the EU proposed adopting more stringent regulations on the level of PM2.5 in line with the latest WHO guidelines. The proposal is one of the stages in the implementation of zero pollutant emissions under the European Green Deal. The purpose of this study was to compare the current limit values for PM2.5 and air pollution in Poland and the EU. The literature related to changes in PM2.5 concentration and the effect on the exposed population was analyzed. An unquestionable benefit from tightening regulations will be the improvement of the health of EU residents. Numerous studies described in the literature prove the relationship between the increased concentration of air pollutants and a higher number of daily deaths and hospitalizations due to cardiovascular and respiratory diseases. Studies described in the literature show that a decrease in suspended dust concentration by 10 μg/m^3 significantly reduces the number of deaths caused by cardiovascular diseases, and a decrease of 15 μg/m^3 may contribute to the extension of life by up to 2 years.

Keywords: PM2.5; ambient air pollution; air quality and health

Introduction

Poor air quality is a global challenge, not only in poor or industrially developed countries. The problem affects every corner of the world, because air pollution depends on the weather and is carried over long distances (Michalak and Szyja 2022). Air protection focuses on reducing the amount of pollutants emitted to the environment to concentration levels that will not cause negative changes in the environment and pose a threat to human health (Juda-Rezler 2016).

Air pollution is a mixture of gases, aerosols, and airborne solids that occur in the excessive levels. Each of such substance can cause health effects, the greater the exposure to a given pollutant. Sources of air pollution are mainly related to the combustion of solid fuels and natural processes such as volcanic eruptions or sandstorms (Andrews et al. 2022; Juda-Rezler 2016)

Particularly dangerous air pollutants are suspended dusts, which are a mixture of organic and inorganic pollutants, such as PAHs, heavy metals, sulfates, ammonium compounds, dioxins, allergens, and many others. Dust has a wide impact on the health of people, animals, plants, and materials. Most often, dust fractions are determined for particles with equivalent diameters below 10 μm – PM10 and below 2.5 μm – PM2.5. PM2.5 particles are a common pollutant found in smoke and smog. Due to their size, they have the ability to penetrate deep into the respiratory system, which causes serious health consequences (Fig. 1) (Andrews et al. 2022; Juda-Rezler 2016). In Poland, in 2020, the largest PM2.5 dust fraction came from the energy sector (93%), of which 73% came from the combustion of hard coal and wood in households (KOBIZE 2021).

Figure 1. Particular size comparison

Poland is a country based on coal for energy, which is why air pollution has one of the highest values in Europe (Michalak and Szyja 2022). PM2.5 emissions in 2020 have decreased by 55% since 1990, a slight decrease in PM2.5 emissions was recorded compared to 2019 year by 0.4%. The biggest problem is in highly industrialized regions, such as the Silesia and Malopolskie voivodeships (KOBIZE 2021).

1. Materials and methods

The work compares the current limit values for PM2.5 and PM2.5 air pollution in Poland and in the world. The literature related to changes in PM2.5 concentration and the impact on the exposed population in the European Union, Poland, and selected countries of the world was analysed.

2. Results

Air pollution and limit values for PM2.5

The World Health Organization (WHO) released its new air quality guidelines (AQG) in September 2021. The report is the first update of the guidelines published in 2005, which is based on research on air quality and its impact on human health. The report describes the harmful effects of even low concentrations of air pollutants on human health, which was the basis for lowering the recommended levels of permissible pollutants compared to the 2005 report (Table 1). WHO recommendations are in no way binding on countries, they are only recommendations that individual governments can incorporate into legislation. The WHO goals are close to the assumptions

Table 1

Recommended 2021 AQG levels compared to 2005 air quality guidelines

Pollutant	2005 AQGs		2021 AQGs	
	Averaging Time		Averaging Time	
	24-hour[a]	**annual**	**24-hour[a]**	**annual**
PM 2.5 [μg/m³]	25	10	15	5
PM 10 [μg/m³]	50	20	45	15
NO_2 [μg/m³]	–	40	25	10
SO_2 [μg/m³]	20	–	40	–
CO [mg/m³]	–	–	4	–
Pollutant	**8h[a]**	**peak season[b]**	**8h[a]**	**peak season[b]**
O_3 [μg/m³]	100	-	100	60

[a] 99th percentile (i.e. 3–4 exceedance days per year).
[b] Average of daily maximum 8-hour mean O_3 concentration in the six consecutive months with the highest six-month running- average O3 concentration.
Note: Annual and peak season is long-term exposure, while 24 hour and 8 hour is short-term exposure.
Based on: WHO 2006; WHO 2021.

of the European Green Deal (EU Green Deal) and the Zero Pollution Action Plan, which gradually tighten the permissible pollution standards. The European Union decided to introduce air quality standards at the level proposed by the WHO. The regulations will gradually be tightened with transitional standards until 2030. A review of the compliance of standards with WHO guidelines will be carried out in 2028. The current directive (2008/50/EC) will be changed, provisions will be added allowing people who have suffered damage to their health due to air pollution to seek compensation if the relevant EU rules have been breached. They will also have the right to be represented by NGOs in collective actions for damages. The proposed change of the directive 2008/50/EC will better clarify access to justice, effective sanctions, and better inform the public about air quality (EEA, WHO 2026; WHO 2021).

The biggest changes proposed by the WHO concern PM2.5, which is the most problematic in terms of exceeding standards in the world. Table 2 shows the current permissible limits for PM2.5 in the air, the average value obtained in 2021 and the place in the ranking of the most polluted countries in 2021 by the IQAir portal (IQAir 2021). Currently, the permissible average annual level in the European Union is one of the highest in the ranking. Among the countries indicated in Table 2, only Norway has 24h standards at the same level as WHO recommendations. On the contrary, Australia has the lowest average annual limit value of 8 μg/m³.

Table 2

Ambient Air Quality Standards for PM2.5 in Poland and chosen countries compared with WHO Guideline Values, statement in the IQAir rank with annual average value in 2021

Country	Air Quality Standards		Measurement results	
	Time interval for PM2.5 [μg/m³]		Rank IQAir	Annual avarage PM2.5 in 2021 [μg/m³]
	24 h	annual		
WHO	15	5	–	–
Poland (same for the EU)	–	20	53[1]	19.1[1]
Norway	15	10	100	7.5
USA	35	12	90	10.3
Australia	25	8	109	5.7
Canada	27	8.8	95	8.5
Japan	35	15	92	9.1
China	75	35	22	32.6
Bangladesh	65	15	1	76.9
Israel	37.5	25	55	18.7

[1] Results for Poland.
Based on: IQAir 2021.

The most polluted region in the world is Asia, with Bangladesh, Pakistan, Tajikistan, next is Chad and India in the top 5 in the IQAir ranking (Fig. 2). The highest bot country in the European Union was Croatia in 35th place, and the second was Poland in 53rd place. The cleanest countries in the European Union were Finland and Estonia.

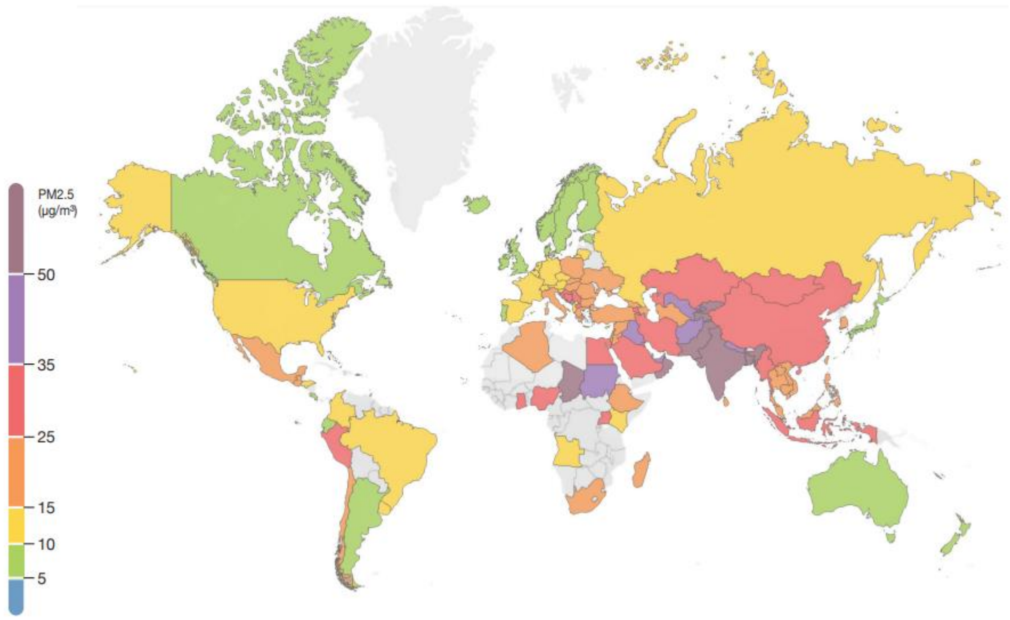

Fig. 2. 2021 global map color coded by annual average PM2.5 concentration (IQAir 2021)

Health effect

Particulate matter is one of the most dangerous air pollutants, which is why their impact on human health is the subject of numerous studies. PM2.5 dust is considered the most dangerous because its particles penetrate the lower respiratory tract and alveoli. Scientific research shows that air pollution with PM2.5 dust causes respiratory system, cardiovascular system, digestive system, and numerous skin and psychological complications (Krzeszowiak and Pawlas 2018). Poor air quality is also responsible for a large number of premature deaths and numerous diseases in Europe. The EEA estimated that particulate matter contributed to 307,000 premature deaths in the EU in 2019 (EEA).

Analyzes by Khomenko et al. (2021) showed that reducing air pollutant concentrations below WHO guidelines will yield significant health benefits. Data analyzed by the same team showed premature mortality due to PM2.5 in European countries at a level of up to 15%. The highest loads recorded in Italy, Poland and Lithuania. Other studies show that each increase in PM2.5 concentration by 0.10 μg/m^3 can cause an

8% increase in cardiovascular disease and increases of mortality among the elderly (Luo et al. 2022). Researchers reached similar conclusions during the adult cohort study "Harvard Six Cities", showing that with a decrease in PM2.5 concentration by 10 µg/m^3 after 10 years, the number of deaths due to cardiovascular diseases is reduced by 27% (Laden et al. 2006). Boldo et al. (2006) stated that reducing the average annual concentration of PM2.5 to 15 µg/m^3 could result in an increase in life expectancy in the range of 1 month to 2 years.

3. Discussion

Reducing the number of diseases and mortality caused by high concentrations of PM2.5 will translate into real expenses for the treatment and rehabilitation of people exposed to air pollution. It is important to strive for the maximum reduction in the emission of particulate air pollutants in order to improve the quality and length of life without disease for the inhabitants of each country.

The estimated changes in PM2.5 air pollution after the tightening of permissible concentrations in accordance with WHO recommendations are shown in Figure 3. Expected changes are visible, especially in Central Europe, where PM2.5 concentrations are expected to decrease by half. Obtaining such results will be close to achieving the assumptions of the European Green Deal.

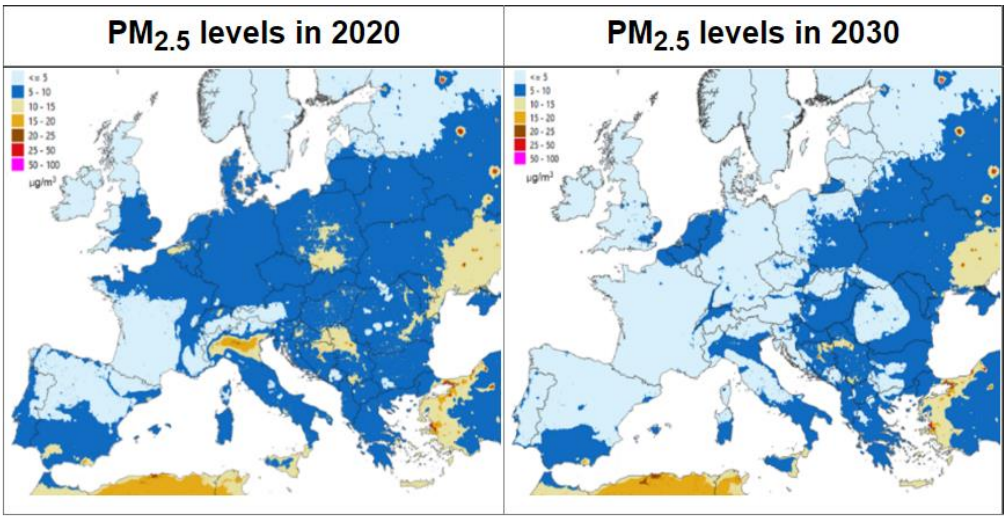

Fig. 3. PM2.5 pollution in Europe in 2020 and estimated pollution in 2030 (after changing the limit in accordance with WHO guidelines) (https://ec.europa.eu/commission/presscorner/detail/en/ip_22_6278)

Obtaining air pollution levels in Poland at the level proposed by the WHO requires the introduction of solutions that will reduce the formation of dust in individual heating systems. Heating boilers must be replaced and efforts must be made to reduce the number of individual solid fuel heating systems by replacing them with a connection to collective heating plants, where possible. Another solution, supported by various subsidies, is thermal modernization of buildings, installation of an ecological heat source based on renewable energy sources, and the use of nuclear energy. Certainly, numerous actions are constantly required to raise awareness of the population in regard to air pollution (Michalak and Szyja 2022). The described activities fall within the framework of a low-emission economy. Other methods of reducing air pollution in cities include the introduction of clean transport zones, encouraging residents to use public transport or bicycles.

The EEA data and science publications shows that earlier tightening of air quality standards has delivered the intended health benefits. Therefore, the introduction of more stringent standards for PM2.5 will reduce the exposure of EU citizens to diseases related to air pollution. Other benefits will be the protection of the natural environment, less air pollution will also benefit plants and animals.

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Quality and management options of washings discharged from swimming pool filters with a zeolite-active carbon bed

Abstract: The high cost of water supply and discharge of washings formed as a result of rinsing filter beds in swimming pool water treatment circuits leads to a search for opportunities to reduce these costs. Depending on the quality of the washings, it is possible to use them for domestic purposes, infiltration to the ground, feeding retention ponds, or other watercourses. Analysis of selected physicochemical parameters was carried out for washings discharged from two pool circuits, equipped with filters with a zeolite-active carbon bed. The results of the analyses were compared with the permissible values included in the regulation on substances harmful to the aquatic environment and conditions to be met when discharging waste water into waters or the ground. It was found that direct discharge of the washings into the surface water was not possible, due to suspended solids amounts above 35 mg/L. The washings samples were subjected to a sedimentation and coagulation process. The high efficiency of both processes and the possibility of discharging the supernatant water (75% of the washings volume) into the water reservoir were shown. An economic analysis (three variants) was also carried out. Variant I assumed the discharge of 100% of the washings into the sewage system, variant II – the reuse of 75% of the washings, and variant III – reuse of 96% washings.

Keywords: quality of washings; swimming pool filters; a zeolite-active carbon bed; economic analysis

Introduction

A swimming pool is a facility equipped with at least one swimming pool basin that has a permanent bank and bottom, its own closed-circuit water treatment system, and sanitary facilities including locker rooms and showers (Act of 18 August 2011). Water consumption in swimming pool facilities is very high. Water is needed for filling swimming pool basins, ongoing replenishment of water losses, rinsing of filter beds, dissolution of reagents, as well as for domestic and household purposes e.g. supplying sanitary facilities, cleaning work on the facility, watering greenery (Lempart and Wyczarska-Kokot 2017).

In Poland the expected average water consumption in an indoor swimming pool per person is 160 L and per a day according to the Regulation of the Minister of Infrastructure of January 14, 2002 (DMI 2002). However, the actual consumption depends on the function and type of the pool, the technological system of water treatment (including the type of filters), the efficiency of the equipment used, the attendance or the standard of equipment of the entire facility (Maglionico and Stojkov 2015; Silva et al. 2021; Pimentel-Rodrigues and Silva-Afonso 2022). The basis of the operation of swimming pool water treatment systems is the filtration process, the main purpose of which is to remove suspended solids of varying degrees of dispersion. Thus, this process is a protection of the further part of the installation from mechanical damage and siltation. Nowadays, pressure (closed) filters, designed and operated according to the guidelines of German standard DIN 19605 (DIN 19605, 2016), are most commonly used in swimming pool installations. In the case of pool water treatment, it is important that the filtration process is accompanied by rapid replacement of water in the pool basin and effective disinfection (Wyczarska-Kokot et al. 2019). The simplest type of filters are single-layer pressure filters, in which the bed is filled with one type of filter material – quartz sand of different grain size. Such a solution was very popular, but as a result of ongoing work to increase the efficiency of filtration, multilayer filters were developed, in which the filter bed consists of two or three layers of different types of materials with different grain size and density (Gosling et al. 2017; Wyczarska-Kokot 2020).

Nowadays, quartz sand, anthracite, activated carbon, beds containing silver nanoparticles with disinfecting effect (Wyczarska-Kokot et al. 2020), glass beds with negative surface charge allowing to additionally remove fine organic pollutants and positive ions from water, e.g. iron and manganese (Dryden Aqua – Innovative water treatment technology; Evans et al. 2002), and zeolite, diatomite, cellulose fibre or perlite beds that effectively remove fine suspended particles, colloidal particles, ammonium ions, halogenated ions, heavy metals and reduce chloramines concentrations in water (Guo et al. 2018; Wasielewski et al. 2018; Włodyka-Bergier et al. 2017). Due to the mentioned properties, in some swimming pool facilities, zeolite bed is used as a base layer (in single-layer filters) and as a filter layer supporting the operation of a layer of quartz sand or activated carbon. The high efficiency of the new filtration systems is related to the high capacity of the used filtration materials for contaminants, and therefore the need for their effective rinsing and, consequently, the management of large volumes of washings (Fouad et al. 2016; Skolubovich et al. 2017; Wyczarska-Kokot and Lempart 2019). The high cost of water supply and wastewater disposal on the one hand, and technological progress and the need to protect water resources on the other hand, have already resulted in conceptual designs for the construction of swimming pool facilities that assume the use of washings. As previous experience and the results of scientific research show, washings, depending on the degree of their contamination or the expected method of their treatment, can be used for watering greenery, flushing toilets, replenishing water losses in the pool circuit or discharging into waters or the ground (DIN 19645, 2016; Liebersbach et al. 2021; Studziński et al. 2021; Wyczarska-Kokot and Dudziak 2022).

The research, carried out to date, on the quality and possibilities of managing the washings mainly includes the washings generated after washing the beds most commonly used in pool water filtration systems, i.e. sand, anthracite and diatomite beds. Zeolite-carbon beds, on the other hand, have so far been very rarely used for pool water filtration. In order to extend the knowledge of the quality and potential use of washings discharged from zeolite-carbon bed filters, the present thematic research was undertaken. The main aim of the research undertaken was to determine the quality and then the possibility of managing the washings discharged from two different swimming pool circuits (a recreational pool and a sports pool), where the water is filtered by zeolite-active carbon beds. An economic analysis of three variants related to the management of water consumed for washing the studied beds was also carried out.

1. Materials and methods

1.1. Characteristics of the tested swimming pool circuits

Water treatment circuits were analysed for the sports pool (SP) with a capacity of 75 m^3/h and the recreational pool (RP) with a capacity of 60 m^3/h. The pools are supplied with water from the municipal water supply system. Two pressure filters with a diameter of 1800 mm were used for water filtration for the SP. Two filters with a diameter of 1600 mm were used for water filtration for the RP. Both circuits used 1200 mm high beds (of which: 300 mm is a layer of zeolite with a grain size of 4–16 mm, 500 mm is a layer of zeolite with a grain size of 1–5 mm and 400 mm is a layer of activated carbon with a grain size of 0.6–2.36 mm). The filtration velocity is 30 m/h. The zeolite bed with a layer of granular activated carbon is washed with water.

To increase filtration efficiency, a coagulant 5% FlockChem Super® (diglin pentahydroxychloride) is dosed into the circulating water before the filters. Correction of pH is carried out with a 50% sulfuric acid solution, and water disinfection is carried out with calcium hypochlorite (HTH Easiflo® system). Treated water is fed into the pools using inflow nozzles located in the pool bottoms. In turn, overflow water from the pools is discharged into compensation tanks from where it is sucked into the filters using a system of pumps. The general scheme of water circulation in the studied swimming pool facility is shown in Figure 1.

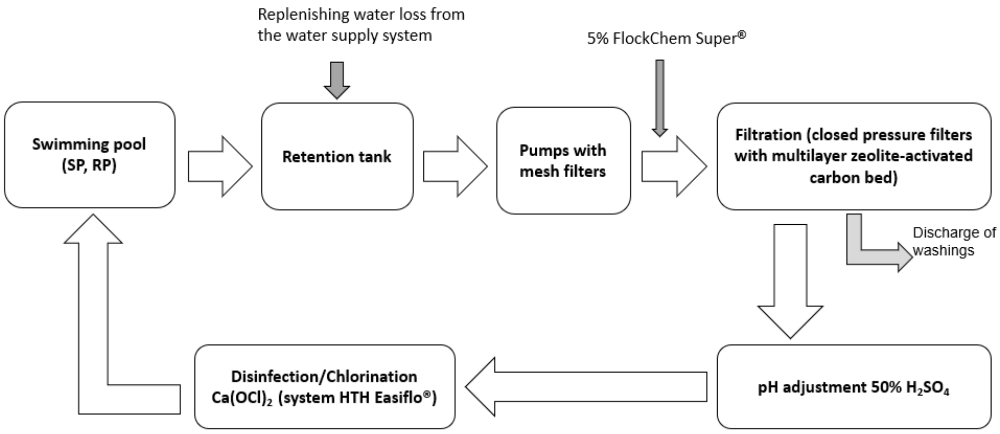

Fig. 1. The scheme of water circulation in the studied swimming pool facility

Both the SP and RP pools are characterized by high bather loads (attendance). From Monday to Friday during school hours, swimming lessons are held for children from nearby schools. While on weekends and in the afternoons, the pools are available to the willing public. In total, the two pools are used by about 540 people a day.

1.2. Washings volume analysis

For proper washing of the pool filter bed, 4 to 6 m^3 of water per m^2 of bed is required, and washing should take place no less than every 3 days (DIN 19643, 2012).

In the case analysed, filters in the SP circuit with a filtration area of 2.54 m^2 and filters in the RP circuit with a filtration area of 2.01 m^2 were washed with water taken from the compensation tank at a rate of 5 m^3 per m^2 of bed. The washing of each bed was carried out only once every 7 days.

The summary of the demand for washing water and at the same time the volume of washings, at different time intervals (a week, a month, a year), is shown in Figure 2.

1.3. Sampling and handling of samples

Samples of washings from the filtration system were collected during the washing of the filter beds in the amount of 5 L each. Sampling was carried out in accordance with the PN-ISO 5667-10:2021-11 standard (Water quality – Sampling – Part 10: Guidance on waste water sampling). Laboratory analysis of three washings samples was carried out. Two samples were taken from the circulation of the RP pool (on: April 5, 2022 and April 6, 2022) and one sample from the circulation of the SP pool (on: April 12, 2022).

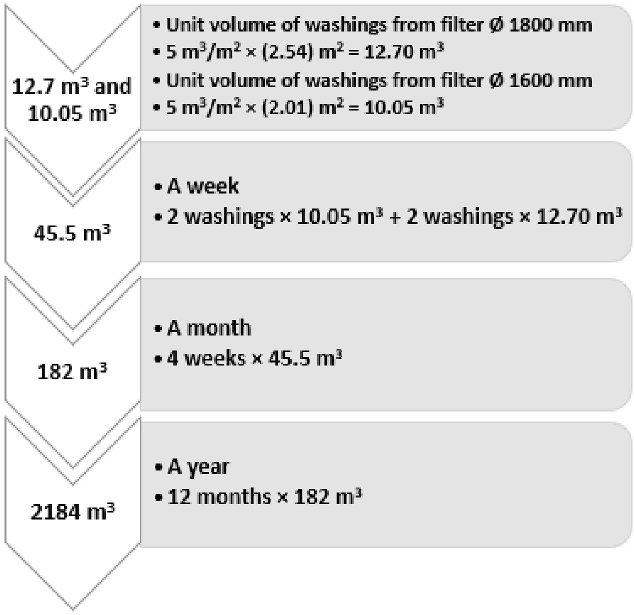

Fig. 2. The summary of washings volume per a week, a month, and a year

The quality of raw washings, the quality of supernatant water after 120 minutes of washings sedimentation and the quality of supernatant water after the washings coagulation process were analysed.

The sedimentation process was carried out under laboratory conditions in the Imhoff funnel (Fig. 3). The coagulation conditions were adopted based on the experience of previous studies on the quality of the washings and, at the same time, as standard for this type of process.

The coagulation process (fast mixing 200 rpm for 1 minute; slow mixing 20 rpm for 20 minutes, and sedimentation for 30 minutes) was carried out in laboratory conditions in the four-stand laboratory mixer (Velp Scientifica) (Fig. 4). A 5% coagulant solution was used FlockChem Super® in doses: 10, 20, 50 and 100 mg Al/L.

1.4. Analysed parameters and methodology of their measurement

Table 1 presents the analysed physical and chemical parameters, the method of their determination, the measuring tool used and the numbers of the standards on the basis of which the measurements were made.

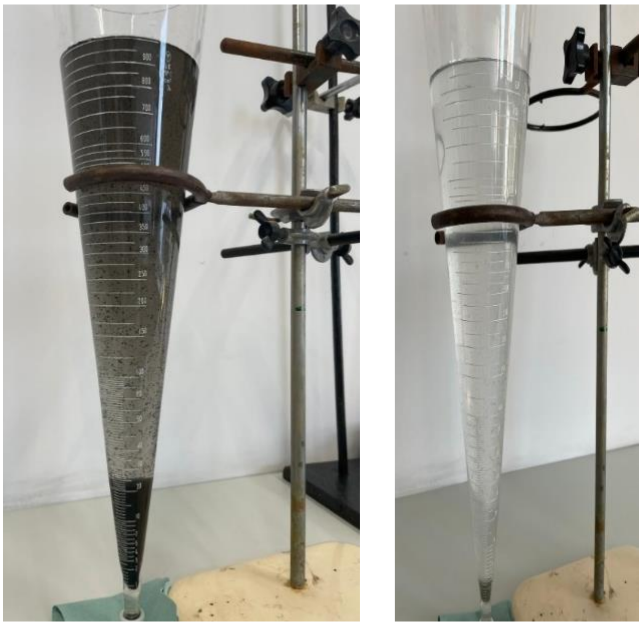

Fig. 3. Sedimentation process in the Imhoff funnel - sample no. 1 (RP) and no. 3 (SP)

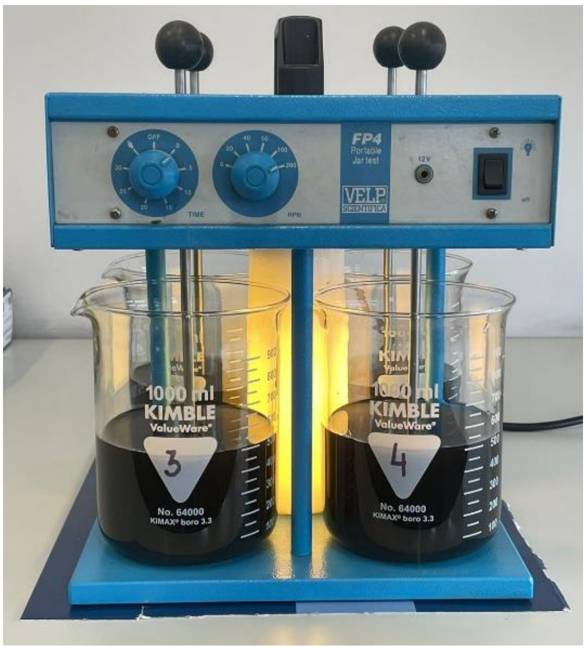

Fig. 4. Coagulation process in the laboratory mixer – sample no. 1 (RP)

Table 1

Washings quality parameters and measurement methods

Parameter	Unit	Determination method	Measuring tool	Standard No.
Total nitrogen	mg N/L	Photometric	Spectrophotometer DR 3900 (Hach®)	PN-EN ISO 13395:2001
Total chlorine	mg Cl_2/L	Photometric	Pocket Colorimeter II (Hach®)	PN-EN ISO 7393-2:2018-04
Free chlorine	mg Cl_2/L	Photometric	Pocket Colorimeter II (Hach®)	PN-EN ISO 7393-2:2018-04
Chlorides (Cl^-)	mg Cl^-/L	Spectrophotometric	Spectrophotometer DR3900 (Hach®)	PN-ISO 9297:1994
COD (Chemical Oxygen Demand)	mg O_2/L	Spectrophotometric	Spectrophotometer DR3900 (Hach®)	PN-ISO 6060:2006
Total phosphorus	mg P/L	Spectrophotometric	Spectrophotometer DR3900 (Hach®)	PN-EN ISO 6878:2006
Aluminium	mg Al/L	Spectrophotometric	Spectrophotometer DR3900 (Hach®)	PN-EN ISO 12020:2002
Turbidity	NTU	Nephelometric	Turbidymetr Eutech TN-100 (Thermo Scientific)	PN-EN ISO 7027-1:2016-09
TOC (Total Organic Carbon)	mg C/L	Catalytic combustion	Analyzer TOC-L (Shimadzu)	PN-EN 1484:1999
pH	–	Potentiometric	SensiON MM150 DL (Hach®)	PN-EN ISO 10523:2012
Sulphates	mg SO_4^{2-}/L	Spectrophotometric	Spectrophotometer DR3900 (Hach®)	PN-C-04566-02:1982
Temperature	°C	Potentiometric	SensiON MM150 DL (Hach®)	PN-C-04584:1977
Total suspended solids (TSS)	mg/L	Spectrophotometric	Spectrophotometer DR3900 (Hach®)	PN-EN 872:2007

1.5. Variants for the management of washings – economic analysis

Wastewater from the studied pools is discharged into the sanitary sewer system. The results of the research contained in this paper may be relevant to the practical solution of the problem of water management in swimming pool facilities and will be of interest to specialists in this field. Depending on the quality of the washings and the technical and investment possibilities of the manager of the swimming pool facility, three variants of washings management were subjected to economic analysis.

- Variant I: discharging 100% of washings into the sewage system,
- Variant II: management of 75% of the supernatant water from washings, recovered in the process of sedimentation or coagulation,
- Variant III: management of 96% of the supernatant water from washings recovered after the use of the SOWA® system, according to the information and

the "savings calculator" provided by the manufacturer of this system (https://sowa.expert).

The following assumptions were made for the calculations:

- washings volume assumed in accordance to the values as in Figure 2,
- price of 1 m^3 of water – 8.08 PLN (based on data from June 8, 2022),
- price of 1 m^3 of discharged sewage – 13.42 PLN (based on data from June 8, 2022).

2. Results

2.1. Results of washings quality analysis

Table 2 summarizes the results of qualitative analysis of the tested samples (No. 1, 2 and 3) of the raw washings (0′) and after 120 minutes (120′) of sedimentation in the Imhoff funnel. Table 3 summarizes the parameters and effects of the coagulation process carried out for the tested washing samples.

Table 2

The results of physical and chemical analysis of raw and post-sedimentation washing samples and permissible values for wastewater discharged to surface water or to the ground

Parameter	Unit	No. 1 (RP)		No. 2 (RP)		No. 3 (SP)		Permissible values in wastewater discharged to surface water or ground (DMMEIN 2019)
		0′	120′	0′	120′	0′	120′	
pH	–	6.55	6.31	6.39	–	6.52	–	6.5–9.0
Temperature	°C	20.2	20.7	20.5	–	20	–	35
COD	mg O_2/L	145	12	98.6	–	63.2	–	125
Total nitrogen	mg N/L	26	8.74	9.05	–	8.81	–	10
Total phosphorus	mg P/L	0.58	0.08	0.03	–	0.13	–	1
TSS	mg/L	571	109	46	31	33	14	35
Sulphates	mg SO_4^{2-}/L	87.9	83.4	85.2	–	75.1	–	500
Chlorides	mg Cl^-/L	352	311	335	–	214	–	1,000
Free chlorine	mg Cl_2/L	0.00	0.00	0.03	–	0.03	–	0.2
Total chlorine	mg Cl_2/L	0.10	0.08	0.15	–	0.10	–	0.4
TOC	mg C/L	2.029*	–	2.517*	–	1.818*	–	30
Aluminium	mg Al/L	0.183	0.044	0.028	–	0.042	–	3
Turbidity	NTU	42.30	18.36	10.84	9.11	13.09	7.06	

*Determination of the TOC in a sample of raw washings after percolation through a soft filter.

Table 3

Parameters and effects of the coagulation process for the tested washing samples

Dose of coagulate [mg Al/L]	TSS in raw washing [mg/L]	TSS in supernatant water [mg/L]	Reduction of TSS	Turbidity of raw washings [NTU]	Turbidity of supernatant [NTU]	Reduction of turbidity	TOC of raw washings [mg C/L]	TOC of supernatant [mg C/L]	Reduction of TOC
No. 1 (RP)									
10	571	31	95%	42.30	10.31	76%	12.029	4.536	no effect
20		30	95%		8.60	80%		3.845	no effect
50		17	97%		6.86	84%		3.870	no effect
100		12	98%		6.49	85%		3.338	no effect
No. 2 (RP)									
20	46	7	85%	10.84	2.58	76%	2.517	2.169	14%
50		5	89%		1.81	83%		1.721	32%
No. 3 (SP)									
20	33	1	97%	13.09	0.94	93%	1.818	1.738	4%
50		0	100%		0.92	93%		1.800	1%

2.2. Results of economic analysis of washings management variants

Table 4 lists the volumes of used and discharged washings according to the proposed variants, and table 5 shows the costs of fees for water used for washing the filter beds, the costs of discharging the washings into the sewage system and the total costs. The profit resulting from the management of washings according to the variants of their treatment is also presented.

Table 4

Volume of managed and discharged washings for the considered variants I, II and III

		Variant I	Variant II	Variant III
Volume of managed washings	m^3/month	0	137	175
	m^3/year	0	1,638	2,097
Volume of discharged washings	m^3/month	182	46	7
	m^3/year	2,184	546	87

Table 5

Costs of water for washing filter beds, costs of discharging washings into the sewage system, total costs, and profit from washings management in variant I, II and III

	Variant	Month	Year
Cost of water for washing filter beds [PLN]	I	1,471	17,647
	II	1,471	17,647
	III	according to the SOWA® calculator*	
Cost of discharging washings into the sewer system [PLN]	I	2,442	29,309
	II	610	7,320
	III	according to the SOWA® calculator*	
Total cost [PLN]	I	3,913	46,956
	II	2,081	24,967
	III	according to the SOWA® calculator*	
Profit resulting from the management of washings [PLN]	I	0	0
	II	1,832	21,989
	III	3,733*	44,797*

*The savings calculator of the manufacturer of the SOWA® system (https://sowa.expert/kalkulator-oszczednosci) does not show the cost of water and sewage discharge, but directly the amount that will be saved with the use of the system including the profit resulting from the recovery of heat energy from the washings.

3. Discussion

The main purpose of the study was to determine the possibility of discharging the washings from filters with the zeolite-activated carbon bed into a retention pond located in a park near the swimming pool facility. Therefore, the results of the study were related to the permissible values, the non-exceedance of which allows the discharge of wastewater into water or ground, and specified in the Regulation of the Minister of Maritime Affairs and Inland Navigation of July 12, 2019 on substances particularly harmful to the aquatic environment and the conditions to be met when discharging wastewater into water or ground (DMMEIN 2019).

As in previous studies on the quality of washings discharged from swimming pool facilities and the possibility of their management (Wyczarska-Kokot and Dudziak 2022; Wyczarska-Kokot and Lempart 2018, 2019), also in this particular case it was found that, in principle, the only parameter limiting the possibility of direct discharge of washings to the natural environment are total suspended solids (TSS) in the amount above 35 mg/L.

In sample no. 1 from the RP circuit, the amount of TSS in the washings was exceeded by as much as 536 mg/L, and in sample no. 2 (RP) by only 11 mg/L. In turn, in sample no. 3, the amount of TSS was 33 mg/L. The large difference in the amount of TSS in each sample was due to the method of collection. Sample no. 1 was taken during the initial washing stage of the filter bed, which is when the amount of TSS washed out is highest. However, samples no. 2 and no. 3 were taken as a mixed average sample and therefore the amount of TSS in them was much lower. Nevertheless, this made it possible to assess the possibility of managing washings with different degrees of contamination (suspension load).

The applied sedimentation allowed to reduce the TSS by 81, 33 and 58% respectively in individual samples. Since only in sample no. 1 the amount of TSS (109 mg/L) after sedimentation exceeded the permissible value, it was advisable to determine the remaining parameters only in this sample. It has been shown that the decrease in the TSS reduces the COD value (by 92%), the content of total nitrogen (by 66%), total phosphorus (by 86%), sulphates (by 5%), chlorides (by 12%), aluminium (by 76%) and turbidity (by 57%).

The content of free and total chlorine in the washings can be considered trace (0.03 mg Cl_2/L). Such low concentrations of chlorine most likely resulted from the sample's standing time. Approximately 12 hours elapsed from the time of collection to the time the samples were transported to the laboratory. During this time, the free chlorine still contained in the washings reacted with the matter contained in the washings.

The applied coagulation process gives the possibility of a significant improvement in the quality of washings in relation to TSS and turbidity, and the possibility of using supernatant water in the amount of approx. 75% of the initial volume of washings (Wyczarska-Kokot 2017; Wyczarska-Kokot and Dudziak 2022; Wyczarska-Kokot and Lempart 2018).

The coagulation process used for sample no. 1 was characterized by the greatest reduction in the content of TSS (from 95 to 98%), basically for all the doses of coagulant used, allowing to obtain in the supernatant water from 12 mg/L (at the highest dose of 100 mg Al/L) to 31 mg/L (at the lowest dose of 10 mg Al/L). A similar relationship was obtained in relation to the turbidity value – a parameter directly dependent on the amount of TSS. For the doses of coagulant used, the reduction in turbidity ranged from 76% (at the lowest dose of 10 mg Al/L) to 85% (at the highest dose of 100 mg Al/L).

An increase in TOC concentration was noted after coagulation in the supernatant water. The largest increase was found in the sample with a coagulant dose of 10 mg Al/L. The concentration of TOC in the raw washings was lower than in the supernatant water after coagulation, as it was determined after the sample was filtered through a soft filter.

For sample no. 2 and no. 3, coagulation was applied with only two doses (20 and 50 mg Al/L) in order to assess the susceptibility of samples with low levels of contamination to this process and compare with the effect obtained for sample no. 1. The reduction in suspended solids and turbidity in sample no. 2 and 3 was above 85%.

The economic analysis in variant I assumed the discharge of the entire volume of washings into the sanitary sewage system. Variant II, based on previous experience (Łaskawiec et al. 2018; Wyczarska-Kokot 2016), assumed the possibility of managing 75% of the volume of the supernatant water in relation to the total volume of the washings after the sedimentation or coagulation process. In variant III, in accordance with the guidelines of the manufacturer system of water recovery from washings and the results of research on this system (Studziński et al. 2021), the possibility of recovering 96% of the water was assumed.

For variant I, the annual cost of water used to rinse the filter beds, together with the cost of discharging sewage to the sewage system (according to prices for water and sewage from June 2022) amounted to 46,956 PLN. Variant II would reduce the annual operating costs to 24,967 PLN, i.e. by 47%. On the other hand, the use of the full SOWA® system (variant III) together with heat recovery from washings would allow for a profit of 44,797 PLN per a year.

However, it is important to remember about the ever-increasing prices of water supply and wastewater discharge. The increase in these prices may also increase the profitability of washings management.

The application of washings to irrigate green areas, for cleaning purposes, for feeding toilet bowl flushers, or discharging to the natural environment not only reduces the operating costs of the swimming pool facility, but contributes to the economic management of water resources.

Summary and conclusions

Based on the analysis of selected physicochemical parameters of three samples of washings from the recreational and sports pool circuits and comparison with the permissible values for wastewater discharged to water or to the ground, it was concluded that direct discharge of the studied washings to water or to the ground is not possible primarily due to significantly higher than permissible amounts of TSS. Therefore, the washings were subjected to sedimentation and coagulation processes, and the effects of reducing the TSS and related parameters were determined. Both processes were shown to be highly effective in treating the analysed washings.

Because the pool facility under consideration generates significant costs related to the water used for washing the filter beds and discharging wastewater into the sewage system, a preliminary economic analysis of water and wastewater management was carried out using three variants of washings management. It was found that operating costs could be reduced by 96% (Variant III with use of the commercial SOWA® system of water recovery from washings). Recovered water could be used, for example, to supplement losses in the swimming pool circuit, for irrigation of green areas, and for domestic purposes.

- Washings from the RP circuit cannot be discharged directly into the waters or into the ground due to the content of TSS (>35 mg/L) and COD (>125 mg O_2/L).
- Total nitrogen, chlorides, total phosphorus, aluminium, pH, sulphates, TOC, total and free chlorine, and temperature in any sample did not exceed the permissible values specified in the regulation on the conditions to be met when discharging wastewater into waters or into the ground.
- Washings from the SP could be directly discharged into waters or into the ground.
- TSS in sample no. 1 (RP) showed the best settling ability. An 81% reduction of TSS was obtained as a result of sedimentation in the Imhoff funnel.
- After 120 minutes of sedimentation carried out in laboratory conditions, it was found that this process reduces the quality indicators of the washings.
- The coagulation process had a positive effect on reducing the content of TSS and turbidity. The use of coagulant doses determined during the tests allowed to reduce TSS below the limit value, i.e. 35 mg/L.
- The greatest reduction in TSS, turbidity and TOC was obtained for the coagulant dose: 50 mg Al/L – in samples no. 2 and no. 3, and for the dose of 100 mg Al/L – in sample no. 1.
- Large differences in the amount of TSS in individual samples indicate the need to pay special attention to the method and accuracy of washings samples collection.
- The obtained results of the amount of TSS in the supernatant water allow us to assume that the washings from the tested filtration systems with a zeolite

-active carbon bed could be used after reducing the amount of TSS. This effect could be achieved by using, for example, a washings settling tank, to which a coagulant would be optionally added. The supernatant water purified in this way could be discharged to surface waters, used for irrigation of green areas or cleaning works in the swimming pool area.

- The analysis of water volume and discharged washings showed that the management of supernatant water is economically justified.
- The use of 75% of the supernatant water would reduce the costs of water supply and sewage discharge from the swimming pool by 47%.
- The use of the system of washings treatment, which allows for the management of 96% of the recovered water, would reduce operating costs in the tested facility by up to PLN 44,797 per a year.

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Grey water as an alternative solution for a sustainable management of water resources – review of good practices in Poland

Abstract: Currently, water scarcity is one of the most important problems in a lot of regions of the world. This is primarily a result of demographic growth due to urbanization and economic development. In addition, problems with access to drinking water are increasing due to the scale of its use for purposes other than food (e.g. washing floors and windows, flushing toilets, watering gardens, etc.). For this reason, action should be taken to reduce the amount of water used and restore it for circulation. One of the effective alternative methods of using water resources is grey water reprocessing and its reuse.

Grey water is contaminated water that is free of faeces. These are mainly sewage generated during household activities such as washing dishes, bathing or washing. Grey water includes all water used in homes and flats with the exception of toilet flush water, which varies greatly in the amount and variety of chemicals and bacteria it contains.

The paper discussed aspects related to reclaimed water management in Poland. In addition, the paper includes examples of good practices of water reuse. The advantages and savings resulting from the application of solutions to restore grey water to circulation are indicated.

Treated water reuse has good potential but is still not widespread in most countries. This is due to various constraints, including technical, economic, social and legal aspects. For example, there is no definition of grey water in Polish law and there are no defined parameters for its quality. Although "grey water" has not been defined in Polish law, it is mentioned in the PN-EN 12056-1:2002 standard concerning gravity drainage systems within buildings. To this end, actions aimed at educating the public and disseminating information on solutions that support sustainable environmental management should be continued.

Keywords: grey water; water reuse; sustainable development; good practices

Introduction

Water is one of the most important resources in the world. Population growth due to increasing urbanization, economic development and climate change are putting increasing pressure on the world's conventional water resources (Mishra et al. 2021). Water scarcity is a problem affecting many countries, not only in Europe but all over the world (van Vliet et al. 2021). This is a problem not only in the context of human health and life, but also causes serious effects on the environment, such as soil degradation, water pollution, which results in a reduction in agricultural production and a threat to biodiversity (Tzanakakis et al. 2020). Actions at various levels are therefore necessary, from investments in water and sanitation infrastructure (European Commission 2020), through effective and sustainable management of water resources, to public education.

Faced with the challenge of ensuring access to water for the entire population, the European Union (EU) has adopted a series of legislation and initiatives to improve water quality, increase its availability, sustainable use of water resources and increase water efficiency across the EU. One of the main priorities of the current EU water policy, which can bring significant economic, environmental and social benefits, is the reuse and recycling of water. In accordance with Regulation (EU) 2020/741 of the European Parliament and of the Council on minimum requirements for water reuse (The European Parliament 2020), there are factors that can improve the EU ability to respond to the increasing pressure on water resources. These factors include: promoting the reuse of treated wastewater, minimising the exploitation of surface and groundwater bodies, limiting the effects of the discharge of treated municipal wastewater, while ensuring a high level of environmental protection. According to Directive 2000/60/CE of the European Parliament and of the Council (European Commission 2000), water reuse, combined with the popularization of the implementation of water-efficient technologies and water-saving irrigation techniques in industry, is one of the additional measures that will help Member States to achieve the objective of the Directive in terms of good status of surface and groundwater bodies in quantitative and qualitative terms. Council Directive 91/271/EEC (Council Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment (91/271/EWG) 1991), which is a "basic measure" within the meaning of the Water Framework Directive, requires the reuse of treated waste water whenever appropriate. In December 2019, the EU announced the European Green Deal (COM no. 640 2019; Smol et al. 2022), a new economic strategy according to which by 2050 Europe should be climate-neutral, resource-efficient and circular (Marcinek et al. 2020), which was also mentioned in the Communication on the circular economy presented by the European Commission in 2015 (COM no. 614 2015; Smol and Szołdrowska 2020).

There are secondary sources of water suitable for reuse, such as household sewage. Household sewage can be divided into two main groups: black water – coming from flushing toilets, and grey water, which, depending on the source, can be divided into water with a low and high pollutant load (Nolde 2000; Al-Jayyousi 2003). The household sewage classification is shown in Figure 1.

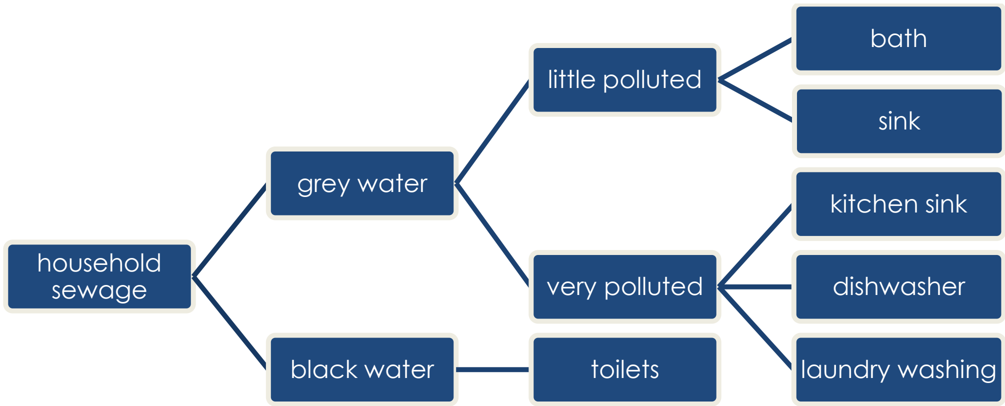

Fig. 1. The household sewage classification (Komorowska-Kaufman and Jaszczyszyn 2016)

This paper focuses on reusing grey water. It is water of anthropogenic origin, i.e. it is created as a result of human activities. It can come from various sources such as bath, sink, kitchen sink, dishwasher, and laundry washing. There are some risks associated with the use of grey water. Before reusing it, it must be subjected to an appropriate cleaning process. Grey water may contain a number of impurities, not only mechanical, such as, for example, rinsing off while washing dishes, but also biological impurities. Living organisms that can get into grey water can cause it to rot during storage, which in turn causes the production of gases that are dangerous to humans. The choice of the appropriate treatment method determines the degree of pollution of grey water and its subsequent use (e.g. for flushing toilets, for irrigation) (Głowacki and Pisarek 2016).

Although the reuse of reclaimed water has great development potential and numerous advantages, it is still not widely implemented in most countries. This may be due to various constraints, including technical, economic and social ones. An analysis of examples of sustainable, circular water management solutions in Poland in various areas of activity (households, enterprises) was carried out.

1. Materials and methods

The paper presents general aspects of water management with particular emphasis on grey water, its reuse and good practices of water management in Poland. This section presents the materials and methods used to prepare this paper. The research was carried out using the Desk Research method (Smol 2021), in four main steps presented in Figure 2.

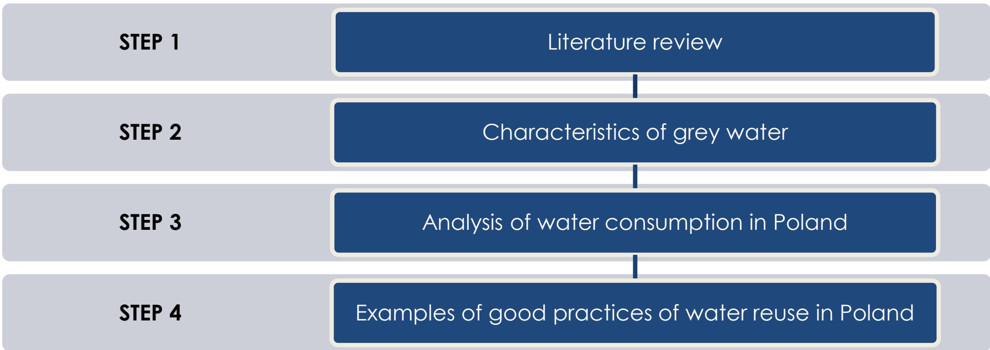

Fig. 2. Research scheme

First, the available literature was reviewed from databases such as Google Scholar, Multidisciplinary Digital Publishing Institute – MDPI, Elsevier ScienceDirect, Elsevier Scopus. Keywords 'water management', 'grey water', 'water reuse', 'good water management practices', etc. were used. The next step was to analyse the problem of water shortage, which is caused, among others, by inadequate management of water resources. Particular attention was paid to the possibilities of reusing grey water and examples of good practices of its reuse in Poland were presented.

2. Results

2.1. Characteristics of grey water

With the prospect of water shortages, the treatment of grey water for various uses plays a very important role. It is believed that grey water has great potential for reuse and application in various sectors of the economy (Oteng-Peprah et al. 2018). The grey water recovery potential depends on many factors, including local geographical and climatic conditions, and legal standards. Access to technology is also an important factor because the variable nature of the grey water source requires a properly selected treatment technology. Grey water contains various types of contaminants such as bacteria, viruses and chemicals (derived from detergents) such as nitrates and phosphates, which can lead to eutrophication (Filali et al. 2022). Grey water should be closely monitored in terms of physicochemical and microbiological parameters. The most important parameters are heavy metals, nitrates and phosphates, pH, oxygen content, chlorine content, number of bacteria and viruses, and the content of organic compounds that can be harmful to the environment.

The qualitative characteristics of grey water are related to its origin. It can vary depending on the chemicals used in households, lifestyle but also the type of distribution network and the quality of the water supply (Oteng-Peprah, Acheampong and deVries, 2018). Selected parameters of grey water were presented based on the review of the available literature (Table 1).

Table 1
Qualitative characteristics of grey water in low- and high-income countries

Parameters	Raw grey water values						Unit
	Low-income countries			High-income countries			
	India	Pakistan	Niger	USA	Spain	Germany	
pH	7.3-8.1	6.2	6.9	6.4	7.6	7.6	–
BOD5	100–188	56	106	86	–	59	mg/l
COD	250–375	146	–	–	151–177	109	mg/l
Nitrates	0.67	–	–	–	–	-	mg/l
TSS	100–283	155	–	17	32	-	mg/l
References	(Parjane and Sane 2011)	(Pathan et al. 2011)	(Hu et al. 2011)	(Jokerst et al. 2011)	(March et al. 2004; March and Gual 2007)	(Merz et al. 2007)	

Monitoring the aforementioned parameters enables the assessment of grey water quality, the efficacy of treatment processes and safeguards against potential hazards to humans, animals, plants and the environmental health. Grey water can be successfully used for flushing toilets, irrigation, washing, cooling industrial equipment and washing cars (Byrne et al. 2020). Using treated grey water to flush toilets can reduce the demand for water from primary sources by up to 30%. Since agriculture is the sector that generates the largest water consumption, from 60 to 80%, the use of grey water for irrigation will reduce the consumption of drinking water by approximately 50% (Al-Hamaiedeh and Bino 2010). However, it should be remembered that before re-use, grey water should be properly treated, because untreated it can pose a threat to people and the environment.

Reuse of grey water is a recommended course of action due to the fact that it accounts for 75% of the total wastewater volume worldwide. This will make it possible to increase the efficiency of water use, which is particularly important in places where its resources are limited. It can also help to reduce water and energy costs and relieve wastewater systems. By properly managing and treating grey water, water availability can be increased and the environmental burden reduced (Rana et al. 2014).

2.2. Polish case study region

Poland is a country characterised by a relatively small level water resources and additionally, they are characterised by seasonal variability and area differentiation of water resources (Gorzelak et al. 2022). Poland is almost entirely within the catchment area of the Baltic Sea (99.7% of the country). The remaining 0.3% of the country's territory is occupied by rivers falling into the catchment systems of the Black Sea (0.2%) and the North Sea (0.1%) (Statistic Poland. Spatial and Environmental Surveys Department 2022). Almost 88% of the total area of Poland lies in the basins of the two largest Polish rivers: the Vistula and the Oder (Kubiak-Wójcicka and Machula 2020). Moreover, there are 9,300 lakes with an area of over 1 hectare (the largest lakes are Śniardwy, Mamry, Niegocin and Wigry, which perform tourist functions and are a source of drinking water for nearby cities) in Poland and over 3,000 km of seacoast. Poland also has significant groundwater resources. It is estimated that in Poland about 70% of water intended for consumption comes from groundwater intakes. According to the latest data, the volume of determined disposable groundwater resources in Poland is nearly 34 million m^3/24h (Przytuła and Mordzonek 2023).

According to data published by the Statistics Poland, Statistical Products Department in 2021 the largest share of water used for the needs of the economy and population is consumed by industry. This is water used for manufacturing, operational, social and administrative needs (excluding water provided to residential structures like plant buildings) and not including water sold or losses within the water distribution system (72,03% annually). The remaining amount of water consumption goes to the exploitation of the water supply network (18,46%) and is used in agriculture and forestry sectors (serves to fill and complete fishponds) – 9,51% (Fig. 3).

Annual water consumption in Poland decreased over the decade from 10.3 billion m^3 in 2010 to 8.8 billion m^3 in 2021. Water consumption for industrial purposes decreased (from 7.7 to 6.4 billion m^3) and for filling and completing fish ponds (from 1.1 to 0.8 billion m3). Agriculture in Poland consumes relatively small amounts of water for irrigation purposes. According to official data, the low water intake is linked to a significant reduction in the irrigated land area. Whereas the use of water for the purposes of exploiting the water supply network has increased (from 1.5 billion m^3 in 2010 to 1.6 billion m^3 in 2021).

Along with the reduction of water consumption in Poland, the amount of sewage produced annually decreased from 9.3 billion m^3 in 2010 to 7.9 billion m^3 in 2021 (Fig. 4).

Most wastewater (82.61%) is industrial wastewater. The rest is municipal wastewater. As in the case of water consumption, the amount of industrial wastewater produced annually decreased (from 8.0 billion m^3 in the base year to 6.5 billion m^3 in 2021); on the other hand, the amount of municipal wastewater slightly increased (from 1.3 to 1.4 billion m^3), which, which belong to grey water.

It should be remembered that the presented statistics refer to water consumption, which is officially reported and registered and the amount of water reuse that is produced and used in Poland is difficult to estimate.

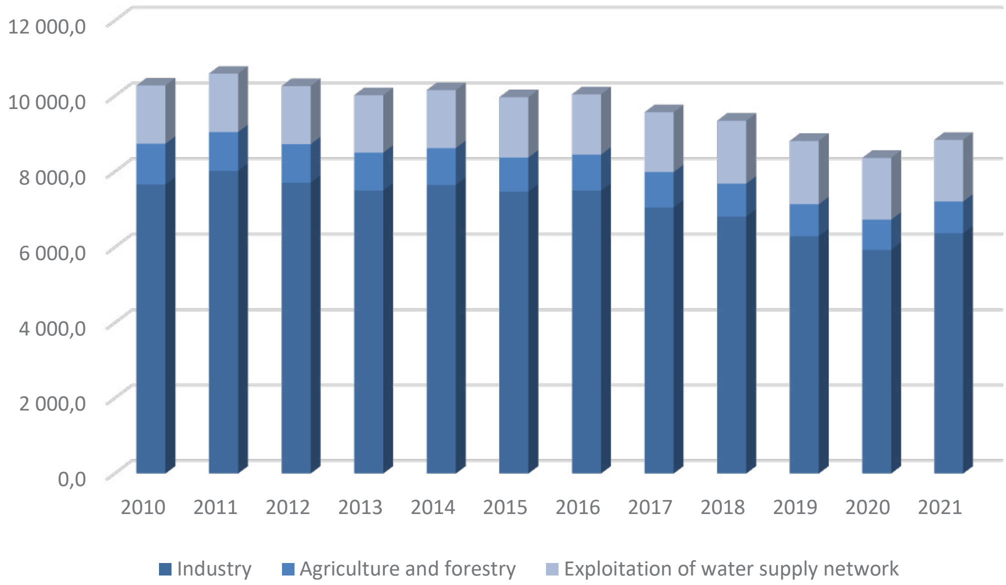

Fig. 3. Water consumption for the needs of the national economy and population (hm^3) (Gorzelak et al. 2022)

Fig. 4. Generation of wastewater (billion m^3) (Gorzelak et al. 2022)

2.3. Good practices of water management in Poland

Sustainable grey water management refers to the collection, treatment, and reuse of grey water in an environmentally friendly and resource-efficient manner (Smol et al. 2020). This includes minimising the use of energy, chemicals, and other resources in the treatment process, and maximising the amount of grey water that is reused.

Some key practices for sustainable grey water management include:

- utilising natural systems and processes, such as sand filtration, biological treatment, and constructed wetlands, to treat grey water (Bolton and Randall 2019),
- using grey water for irrigation in a way that is compatible with the local climate and soil conditions, and that does not promote the growth of invasive or harmful plant species (Van Mechelen et al. 2015),
- incorporating grey water systems into the overall design and planning of a building or community, to optimize the collection and distribution of grey water (Lucy et al. 2010),
- monitoring and evaluating the performance of grey water systems over time, to identify areas for improvement and to ensure that the systems continue to function effectively (Adamczewska-Sowińska et al. 2016),
- collaborating with other stakeholders, such as local governments, utilities, and community groups, to promote sustainable grey water management practices (Dhakal and Chevalier 2016),
- choosing grey water treatment technologies that are low-maintenance and easy to operate, to minimise the need for specialized skills and resources (Elhegazy and Eid 2020),
- using grey water in a way that maximises its value, such as using it for irrigation, flushing toilets, or other non-potable uses (Głowacki and Pisarek 2016),
- regularly maintaining and inspecting grey water systems to ensure they are functioning properly and to prevent contamination (Massoud et al. 2009),
- identifying the sources of grey water in home or building and collecting it in a separate tank or cistern (Marinoski and Ghisi 2019).

The part of paper presents examples of good practices in the context of sustainable management and reuse of water in selected buildings located in Poland. It needs to be highlighted that there is no definition of grey water and no quality requirements in Polish law. However, grey water is mentioned in the PN-EN 12056-1:2002 standard concerning gravity drainage systems within buildings. In this document, grey water has been defined as wastewater that does not contain feces and urine (PN-EN 12056-1:2002, 2002).

2.3.1. Grey water management system in Generation Park X in Warsaw

Generation Park X is a mixed-use development located in Warsaw, Poland. The development is being built on the site of the former Xawery Dunikowski steelworks and includes residential, office, and commercial space. The project is being developed by Ghelamco, a real estate developer based in Belgium. One of the key features of Generation Park X is its focus on sustainability (Grey water management system in Generation Park in Warsaw 2023).

In 2017, in the Generation Park X, the investor Skanska Property Poland installed a complete grey water recycling system (Green Water Solutions 2023). The patented solution allowed to obtain good parameters of the grey water membrane, ensuring good quality, clarity and odorlessness of water suitable for reuse by the building's tenants. Water recovered from showers and washbasins is reused to flush toilets in the facility and to water the greenery around the building. In the recycling process, grey wastewater is successively subjected to sedimentation, aeration and membrane ultrafiltration. The entire system is maintenance-free and does not require servicing more than once a year. The process is controlled by a control cabinet ensuring flow at appropriate time intervals through all stages of purification. The entire Generation Park complex has become the most efficient office complex in terms of water recycling in the region of Central and Eastern Europe, with the possibility of recycling almost 15,000,000 liters of grey water per year (Grey water management system in Generation Park in Warsaw 2023).

Benefits of implementing good practice (Green Water Solutions 2023; Grey water management system in Generation Park in Warsaw 2023):

- recycling of grey water at 40,000 liters per day,
- GreenLife system allows the recovery of 100% of the water,
- reducing the amount of waste water discharged by the building,
- reduction of water consumption from the water supply system,
- reduction of building maintenance costs.

2.3.2. Grey water recycling at Gołębiewski Hotel

Gołębiewski Hotel is a large hotel and spa resort in Poland. It is a 4-star hotel, situated in Karkonosze National Park. Hotel has a commitment to sustainability and environmental protection.

The use of grey water in the Gołębiewski Hotel takes place thanks to the use of a water recovery system. Water drained from the second and third rinsing of the washing process through the sanitary installation goes to the filter, where it is cleaned of chemicals and then pumped to prepared tanks. Purified water is reused during the next washing.

Grey water drained from the hotel's washbasins, bathtubs and shower trays is transported through filters to tanks to remove detergents and neutralize impurities. Part of the water goes to the sewage system, and part is recovered and used to flush toilets in hotel rooms. Thanks to the applied solutions, savings are achieved in the functioning of the hotel complex.

Benefits of implementing good practice (Dual sewage system for grey water (separate from toilets) on the example of the Gołębiewski Hotel in Karpacz 2023):

- cost minimalisation by 20–25%,
- water recovery at the level of about 40%,
- reuse of water in the initial stages of washing,
- reuse of 200 out of 500 liters of water from single wash process.

2.3.3. Grey water recycling installation in the Hotel Radisson Blu Hotel & Residences

The membrane system implemented at the Radisson Blu Hotel & Residences is the center of the GreenLife GWI 20.2-20 000 recycling plant. The selected solution is used for slightly contaminated sewage from showers, bathtubs and hotel washbasins. The technology of membrane biofilters used in the GreenLife installation ensures the total separation of biomass from purified grey water. Thanks to this, it is possible to recover almost 100% of water, free of solid fractions and completely purified of bacterial and virus residues.

The cleaning process consists of a biological cleaning phase and ultrafiltration (MBR membrane bioreactor). The water is then stored in a purified water tank. Implementation of recycling installation allows for daily treatment of the amount of sewage dictated by the demand. The recycling system covering an area of approximately 50 m2 was adapted to the special requirements of the hotel, which has 158 rooms and 68 suites. With a grey water recycling capacity of 20 m^3 per day, most high-quality water is recovered and used for flushing toilets, cleaning, watering greens, and other purposes that do not require drinking water quality (Grey water recovery systems in the hotel industry: New Radisson Blu in Zakopane focuses on sustainable management of water resources 2023).

Benefits of implementing good practice (Radisson Blu Hotel & Residences Zakopane – grey water recycling 2023):

- almost 100% of water recovery from showers, bathtubs and hotel washbasins,
- use of reclaimed water for flushing toilets, cleaning, irrigation of green areas,
- recycling 20,000 liters of water from hotel facility,
- lower consumption and reduction of expenses on mains water.

Conclusions

Given the importance of conserving water resources, grey water, which is wastewater generated from activities such as washing dishes, clothes, and bathing, must be considered as an alternative water source. The paper presents provides various aspects related to grey water management in Poland, where good practices that demonstrate how grey water can be effectively reused. The good practices presented in the paper illustrate the potential of grey water as a valuable resource for the sustainable management of water resources in Poland. By reusing grey water, we can reduce the demand for fresh water and help to conserve water resources, while also reducing the amount of wastewater generated and the burden on wastewater treatment systems.

It is important to note that regulations and guidelines in Poland may change over time, so it is important to stay informed and up-to-date with the latest best practices and regulations for grey water management in the country.

Overall, grey water reuse has the potential to be an effective solution for sustainable water management in Poland. However, it requires greater awareness and support from policymakers, water utilities, and the general public. Thanks this, grey water reuse has the potential to play a significant role in sustainable water management in Poland and beyond. More efforts are needed to promote the benefits of grey water reuse and to overcome the technical and regulatory barriers to its implementation.

In conclusion, it can be acknowledged that the reuse of grey water as part of water resource management is an economical and environmentally friendly solution. In general, all aspects related to grey water depend on public response, regulation and implementation of proper systems by encouraging households to install grey water treatment systems.

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Iceland
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Environmental, economic and social assessment of water reuse

Abstract: In the recent years, the problem of the deepening water deficit in the world and its impact on the natural and social environment is observed. This paper deals with issues related to the recovery and reuse of water in various sectors of the economy. The main purpose of this paper is to present the importance of water reuse and its assessment in environmental, economic and social terms. It also discusses the materials and methods used to carry out environmental, economic and social analysis. One of the most frequently used methods is the life cycle sustainability assessment (LCSA), which combines three types of aspects: environmental life cycle assessment (LCA), economic related to investment costs-life cycle costs (LCC) and the most difficult to assess, social aspect-social life cycle assessment (S-LCA). Examples of conducted assessments of the analysed aspects are presented both for cities in Poland and abroad. It could be stated that water reuse methods, in accordance with the circular economy policy, are constantly developing, preventing irrational management of water resources.

Keywords: water reuse; circular economy; environmental assessment; economic assessment; social aspects

Introduction

Water reuse is a key issue from the point of view of arguably the security of water supply for society around the world (Ramm 2022). In recent years, water availability per capita has been decreasing as a consequence of population growth, and currently it varies significantly by region. However, contrary to appearances, water stress does not occur only in countries such as Asia, Africa or America. According to United Nations Educational, Scientific and Cultural Organization (UNESCO) 2023 report "Partnerships and cooperation for water", a significant decrease in global per capita internal renewable water resources (IRWRs) was observed between 2000 and

2018, reaching 20%. The highest change was recorded in countries with the lowest per capita IRWRs, as regions located in Sub-Saharan Africa (by ~41%), Central Asia (by ~ 30%), Western Asia (by ~29%) and North Africa (by ~26%). In Europe, an observed decrease was about 3% (UNESCO, 2023).

It is worth to notice that there are different types of water stress. There is physical water stress (Zhao et al. 2015), that is determined by surface and/or groundwater availability (that are mainly affected by varying conditions of climate in a given region), ecological requirements, as well as human behaviours. Moreover, in many countries economic water scarcity (Liu et al. 2017) was also reported. It covers situation in which sufficient water volume is available to meet human and environmental needs, but there is limited access to those water resources due to a lack of water infrastructure or inadequate water resources management.

There is significant need to protect water resources access to current and future generations, according to sustainable development (SD) principles (United Nations, 2015). Therefore, in recent years, the role of water reuse from various sources (sewage, rainwater, etc.) has been increasingly emphasised in order to recycle water and reuse it if possible. Water can be recovered by using traditional methods of water purification, including physical, mechanical and biological, or by using integrated processes that combine the above-mentioned methods (Smol et al. 2023). It is very important to apply the appropriate criteria for the selection of the water reuse method, so as to maintain a balance between environmental, economic and social aspects. Therefore, analyses on these factors should be carried out for infrastructure dedicated to water reuse from various sources. Paper presents an overview of different methods of water reuse assessment – environmental, economic and social. Moreover, it underlines an importance of water reuse, and presents different methods of water reuse, including use of reclaimed water for various purposes - economic and agricultural.

1. Materials and methods

The research includes the analysis of the state of the art. The main objective of this state of the art analysis was to characterise importance of water reuse, identify different methods of water reuse, including use of reclaimed water for various purposes – economic and agricultural. There is also overview of different methods of water reuse assessment – environmental, economic and social. This research was realised with the use of the desk research method (Smol 2021). A comprehensive analysis of various data sources was conducted. They focused on the following areas: municipal wastewater plants, industrial plants, agriculture and circular economy. The reviewed databases included official EU (European Union) documents (regulations, directives, communications, working documents and reports), as well as available peer review publications available in selected scientific databases, including Elsevier

Scopus, Baz-Tech, Springer Nature, MDPI – the Multidisciplinary Digital Publishing Institute, and Google Scholar. Literature items were selected based on a list of keywords, which are associated with the assumed objectives. List of keywords included: "circular economy (CE)", "water reuse", "municipal wastewater", "environmental assessment", "economic assessment", "social assessment". Due to increasing significance and popularity of CE, waste management and wastewater management in the last decade, a preliminary analysis resulted in significant amount of documents and papers. A significant part of found documents and papers were rejected due to a lack of connection with water reuse. The final data obtained were extracted, which allowed for selection of most appropriate information, from each item. The data obtained were basis for presentation of results and discussion, that are described in sections below (Smol 2021).

2. Results

This section shows importance of water reuse, and possible sources of reclaimed water, the selected methods of environmental, economic and social assessment of water reuse infrastructure and/or methods, and selected examples of environmental, economic and social assessment of water reuse solutions in Poland and aboard.

2.1. Water reuse importance

As previously stated, ensuring the security of the water supply is a fundamental aspect of EU policy. The increasing demands associated with economic growth, development, and population expansion pose a significant threat to water resources, putting them at risk of depletion. All sectors of the economy – municipal, industrial and agricultural use significant amounts of water for various purposes (Smol et al. 2020).

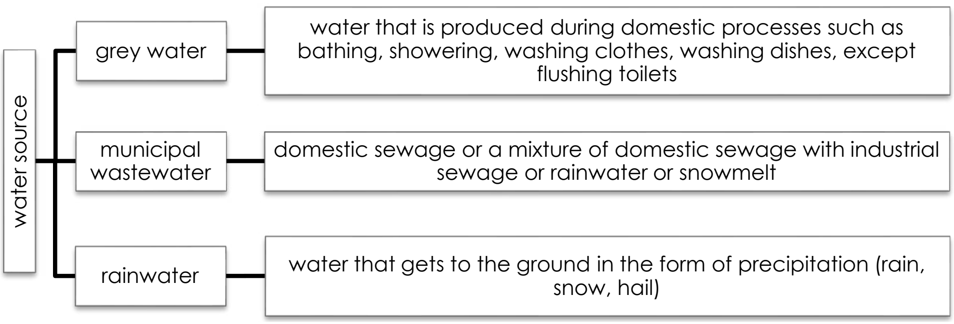

Fig. 1. Potential sources of water for reuse (Stec and Słyś 2017; Helmecke et al. 2020)

One way to deal with the problem of water availability is to reuse water from different sources. Potential sources of water reuse are shown in Figure 1.

2.1.1. Grey water

In an average household, grey water that is including all wastes except toilet waste (blackwater), accounts for 50 to 80% of the daily wastewater generation. They are characterised by a low proportion of organic matter and a large volume. Their reuse could bring many benefits, such as increasing the resilience and adaptability of local water systems, reducing transport costs and achieving EU sustainability goals. One of the risks of grey water reuse is the variability in composition, which depends mainly on their flows, climatic and socio-cultural influences and the original water source (Gross et al. 2015). Grey water contains many different types of contaminants such as solid particles, colloidal materials, dissolved organic and inorganic substances, pathogens. The presence of pathogenic pollutants in grey water is usually much lower than in municipal wastewater – their number is presented as similar to that of secondary treated municipal wastewater. However, even such an amount can pose a serious threat to the health of its users. The presented threats to the reuse of grey water make it necessary to adapt the technology of their treatment, taking into account the method of their subsequent use (Van de Walle et al. 2023). Currently, there are many technologies for reusing grey water from simple processes (filtration and disinfection) to more complex ones (advanced physicochemical and biological processes) (Pidou et al. 2008).

2.1.2. Municipal wastewater

Municipal wastewater is one of the most important source of water for reuse. Due to economic growth and development, the number of wastewater treatment plants in the EU is increasing, which consequently leads to an increasing amount of wastewater flowing into treatment plants, which can be reused for various purposes, thus reducing the use of fresh water (Ramm and Smol 2023). As in the case of grey water reuse, the selection of treatment technology depends on the characteristics of the wastewater flowing to the treatment plant. Not all wastewater treatment methods are able to completely remove all impurities from water. New technologies must adapt to the emergence of newer and newer pollutants and new strategies of the EU regarding the protection of water resources. The right wastewater treatment technologies have been proven to achieve almost any quality level required, including very demanding applications such as drinking water supply. However, advanced water treatment processes are associated with higher costs and higher energy consumption. Therefore, treatment levels are usually tailored for a specific purpose to achieve the required water quality standard (Helmecke et al. 2020). Water for reuse must meet specific quality standards set by the relevant government authorities or institutions responsible for regulating the use or discharge of wastewater (Yang et al. 2020).

2.1.3. Rainwater

The environmental impact of urbanisation and the need to provide water services to the urban population, such as water supply and wastewater management, have significantly affected the hydrological cycle. Effective rainwater management poses a significant challenge for the majority of contemporary cities experiencing continuous urban densification. Adverse changes in the hydrology and climate of urban watersheds have led to the development of innovative approaches such as sustainable rainwater management. One of such solutions is the recovery of rainwater and its utilisation for various purposes in many sectors of the economy.

The collection and use of rainwater brings specific benefits for sustainable development, contributing to the transformation towards circular economy. In addition to the environmental benefits of using rainwater, there are also economic benefits, which are primarily influenced by the possibility of saving tap water, capital expenditures and operating costs incurred during the period of system operation (Stec and Słyś 2017).

For effective water reuse, appropriate treatment and disinfection technologies are required to remove contaminants and ensure safe water use. Possibilities for using reclaimed water include agricultural irrigation, industrial reuse, groundwater replenishment, municipal, firefighting and street cleaning applications, as well as recreational and environmental uses (Helmecke et al. 2020). The European Commission emphasises that the reuse of grey water and rainwater can lead to a reduction in drinking water consumption by 5% by 2050 (BIO Intelligence Service 2012). Reusing waste water to irrigate fields can also help recycle plant nutrients such as nitrogen, phosphorus and potassium (Smol and Szołdrowska 2021). Depending on the purpose of use, reclaimed water can be divided into two categories: reuse for consumptive purposes, which means the use of water after appropriate treatment to supplement drinking water in water systems, and reuse for non-consumer purposes, which includes a variety of uses such as irrigation of green areas, flood protection, recreational purposes in municipal areas, as well as industrial use, especially in cooling processes and closing technological water circuits, and agricultural use. The most common use of reclaimed water is agricultural irrigation. Especially in regions where water shortage occurs (Gromiec 2020).

2.2. Methods of environmental, economic and social assessment

Assessment of environmental aspects is the most important activity for the implementation of the environmental management system according to ISO (International Organisation for Standardisation) 14001.

Assessment of environmental aspects include mainly:
- air emissions,
- water discharges,
- waste management,
- use of raw materials and natural resources,
- other issues related to the local environment and local society.

Descriptive and point methods are used to assess environmental aspects. The descriptive method gives the considered parameters the probability of the occurrence of the event and its impact by means of graded descriptions. On the other hand, the point method consists in the fact that the probability of the occurrence of the event and its consequences as well as the significance of the parameters are replaced with the assigned number of the point key (Ligus et al. 2013).

Socio-Economic Impact Assessment (SEIA) assesses socio-economic costs against socio-economic benefits. This method consists in assessing the impact of the indicators used and proposing rational methods of data collection in order to reduce the negative effects and increase the benefits of the changes that have taken place. It provides comprehensive results on the potential financial and social impact and discuss comments and possible responses to the proposed changes (Tišma et al. 2022).

Environmental and Social Impact Assessment (ESIA) identifies potential impacts on the environment and communities and minimises the harmful impacts of a project's area and society, potentially maximising benefits (Tišma et al. 2022).

In recent years, one of the most popular method for assessment of infrastructure and/or methods in environmental engineering is the life cycle sustainability assessment (LCSA), that covers three types of impacts: environmental, economic and social (Larsen et al. 2022). The constant effort in finding ways for these aspects to coexist supports the concept of sustainability development (Tkaczyk and Kuzincow 2014). Aspect of the life cycle sustainability assessment is presented in Figure 2.

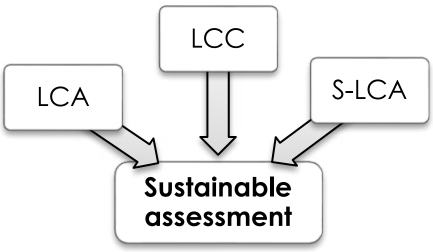

Fig. 2. Aspects of the life cycle sustainability assessment (Tkaczyk and Kuzincow 2014)

The assessment of the environmental aspects of the product throughout its life cycle is carried out through the use of environmental life cycle assessment (LCA). In accordance with the guidelines contained in the ISO 14040 and ISO 14044 standards, (environmental) LCA is carried out in a series of four stages. These phases are usually interrelated and dependent on each other (United Nations Environment Programme 2011).

There are various computer software, both free and commercial, have been developed to perform LCA analysis, for example SimaPro, Gabi, Umberto and openLCA.

There are two types of LCA studies for wastewater treatment. Life cycle assessment supporting comparisons and selection of technologies in terms of environmental impact. The second type, on the other hand, focuses on taking into account the different steps of the LCA methodology itself (i.e. objective and scope, inventory, impact assessment and interpretation) in order to improve the reliability of the LCA results. Stages of LCA are shown in Figure 3 (Rashid et al. 2023).

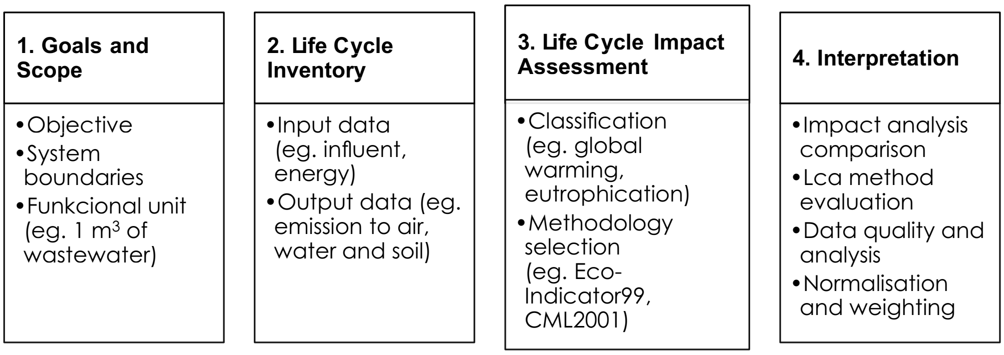

Fig. 3. LCA stages (Rashid et al. 2023)

The life cycle cost analysis (LCCA) method was developed in the United States (U.S.) in the 1960s and was implemented by the U.S. Department of Defense for public procurement. LCC analysis is used in various economic sectors, including energy, industry, transportation, construction, infrastructure and pump technology, and many others. In addition, it serves as a valuable tool for both decision-making and management purposes. LCCA is a costing method that takes into account not only the initial capital expenditures, but also operating costs over the life of the facility. Using this methodology, it is possible to compare different investment options to determine the most financially beneficial option. LCCA can be performed using the following formula (Stec and Kordana 2014).

$$LCC = INV + \sum_{t=1}^{i} (1+r)^{-1} \cdot K_E \tag{1}$$

where:

INV – investment expenditures [PLN],
K_E – operating costs [PLN],
T – duration of LCC analysis,

r – fixed discount rate,
t – consecutive year of using the installation.

Social and Socio-Economic Life Cycle Assessment (SLCA) serves as a method of assessing the potential social impact of products, in particular examining their social and socio-economic aspects throughout their life cycle. This life cycle includes the stages of extraction and processing of raw materials, production, distribution, use, reuse, maintenance, recycling and final disposal. The SLCA aims to complement the traditional LCA by considering not only environmental factors but also the social and socio-economic dimensions. It can be used independently or in conjunction with an LCA (Koper 2016).

2.2. Environmental, economic and social assessment of water reuse

This section provides revision of environmental, economic and social assessment of different examples of water reuse.

2.2.1. Environmental assessment of water reuse

Water reuse system in an industrial park in China

The rapid expansion of China's industrial parks has seen high emissions and high resource consumption. Water reuse can contribute positively for saving fresh water and reducing pollution. Advanced treatment, using chemicals, materials and energy, is usually added to standard wastewater treatment methods to obtain reclaimed water. Tong et al. (2013) conducted a comparative life cycle assessment, to quantify the environmental impact of reusing treated wastewater in industrial parks. Four scenarios were considered: wastewater is treated and discharged, 20% and 99% of wastewater is treated and reused as industrial process water, and treated wastewater is used in horticulture. The inventory data was covered the wastewater management plant and the reuse of the industrial park. Environmental impacts were assessed using the CML2001 methodology, in the GaBi database version 4.3. (Tong et al. 2013). The diagram of the scenarios is shown in Figure 4.

Scenario analysis shows that the third stage of wastewater treatment (reverse osmosis process and electrodeionisation process) had the greatest environmental impact. The greater credit from avoiding traditional industrial production of deionised water could help to minimise this problem. A variant with a higher water reuse rate minimises environmental impact. Reusing water in the industrial park is recommended, from point of view of saving water resources, as the world is threatened with water deficiency (Tong et al. 2013).

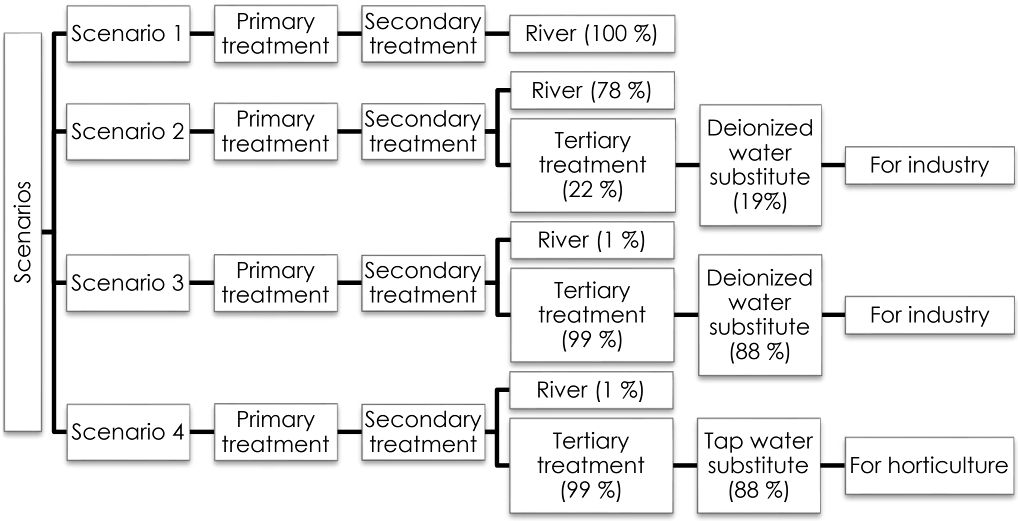

Fig. 4. Scenarios analyzed (Tong et al. 2013)

Wastewater resource recovery technologies in Copenhagen

Valverde-Pérez et al. (2015) have conducted the LCA assessment at the Lynetten wastewater treatment plant in southeast Copenhagen, Denmark. The environmental impact of recovering and reusing wastewater resources in agricultural and aquifer recharge was evaluated quantitatively. The study started from the entrance to the treatment plant, the TRENS side stream process, the transport of treated water through a pressure pipeline and the final application. TRENS system was constantly evolving method of recovering raw materials from wastewater. This technology combines an advanced system of biological elimination and recovery of phosphorus (EBP2R) with a photobioreactor (PBR) to cultivate green microalgae under optimal growth conditions. This technique recovers both nutrients and reuse water from wastewater, which is absorbed and encapsulated in the algal biomass (Valverde-Pérez et al. 2015). The construction and operation phases were also assessed. The assessment did not take into account the end-of-life phase of the wastewater treatment plant and the TRENS system. The operational phases included direct emissions (gaseous emissions and treated wastewater) and indirect emissions (chemical production and power generation). The functional unit was 1 m3 of incoming wastewater. This is due to the fact main function of wastewater treatment systems, with or without TRENS side streams, was to provide adequate water quality for human health and the environment through additional fertigation and groundwater recharge. The LCA was conducted using the Environmental Assessment System for Environmental TECHnologies (EASETECH). Materials were processed and material flows were identified. They were essential for evaluating environmental technologies (Fang et al. 2016). The analysis of wastewater reuse scenarios is presented in Figure 5.

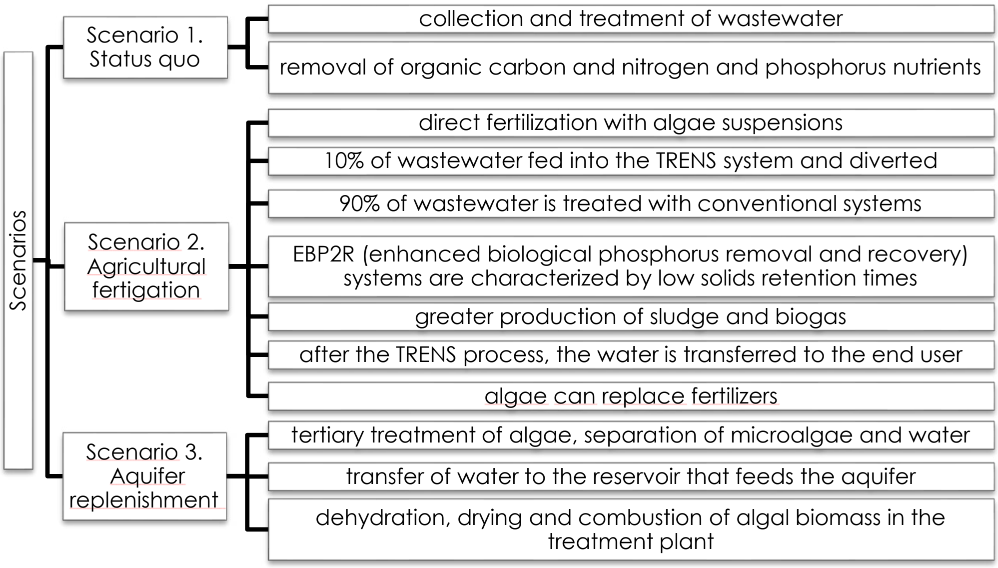

Fig. 5. Scenarios analyzed (Fang et al. 2016)

The study demonstrated the usefulness of applying the EASETECH mass-based and substance-based LCA model in the early development of new wastewater resource recovery technologies. The most important conclusions include geographic location, water demand and the impact of the overall system on the operation of existing wastewater treatment plants in the area should be taken into account when assessing the actual efficiency potential. The TRENS project has been shown to reduce global warming by 15% and marine eutrophication by 9% compared to current levels. Due to the selected end-uses of TRENS products, the greater environmental impact is associated with the categories of ecological and human toxicity, highlighting the need to expand systems beyond clean water and resource recovery technologies (Fang et al. 2016).

Geographic location, water demand and the impact of the overall system on the operation of existing wastewater treatment plants in the area should be taken into account when assessing the actual efficiency potential. The TRENS project has been shown to reduce global warming by 15% and marine eutrophication by 9% compared to current levels. Due to the selected end-uses of TRENS products (nitrogen, phosphorus, water), the grey water environmental impact is associated with the categories of ecological and human toxicity, highlighting the need to expand systems beyond clean water and resource recovery technologies. Reduction of nitrogen compounds in wastewater and nitrogen (N_2O) emissions from nitrification and denitrification processes in TRENS systems makes the efficiency of wastewater treatment plants better. The benefits of TRENS are limited, as the exchange of fresh water and fertiliser needs is limited but increases in proportion to the increase in resource requirements. The

LCA identifies the impact of the design and operation life cycle as an opportunity for improvement, especially for photobioreactor (PBR) projects, as opposed to the assumed life cycle of traditional wastewater treatment plants. With the LCA results, technology developers can proceed with further analysis e.g. N_2O emissions during PBR operation or evaluation of technology options e.g. closed or open PBR connections (Fang et al. 2016).

2.2.2.Economic assessment of water reuse

Economic analysis of the grey wastewater utilisation system

The economic analysis was carried out for the grey water and/or rainwater drainage system in a house of a family of four. The analysis assumed that in systems containing both grey and rainwater, wastewater comes from two washbasins, a bathtub, a shower and a washing machine. Due to the fact that wastewater was collected in the tank, it was equipped with a grey water treatment system. Grey water went to pre-filtration and removal of surface impurities, which is important before entering the bioreactor. Activation of sludge and aeration cause biodegradation in the bioreactor. The final stage of purification was ultrafiltration in a membrane module. The purpose of automatic pumps was systematic desludging. Then grey water was sent to a second tank to treat the rainwater. After cleaning, it was pumped to a second tank. It was then used for flushing the toilet or irrigating the garden. The rainwater tank had a filter to remove impurities and a pump to pump the treated water into the house. The system was managed by a control unit. It delivered a treated water to the source in question, with constant operation of the system. It was connected to the tap water supply system, as this could ensure a constant supply of water, in case the recycled water runs out (Dobrzański and Galoch 2019).

The economic analysis took into account the number and type of sanitary utensils, the frequency of their use and the amount of wastewater. The amount of reclaimed water and user demand were also determined (Dobrzański and Galoch 2019). The scenarios analysis of connection to the water source and wastewater receiver is presented in Figure 6.

Simple payback time (SPBT) was determined by the following formula (Dobrzański and Galoch 2019).

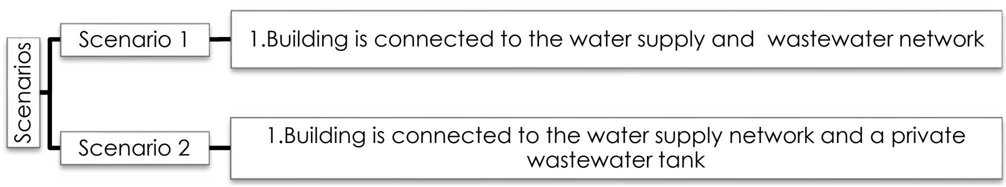

Fig. 6. Scenarios analyzed (Dobrzański and Galoch 2019)

$$SPBT = \frac{K_s}{Z - K_E} \quad \text{[years]} \tag{2}$$

where:

K_s – cost of system [PLN],
K_e – total exploiting costs [PLN/year],
Z – profit obtained from the installed system [PLN/year].

Total cost:

- material costs,
- installation costs,
- commissioning of the water reuse system.

Operating costs:

- water pumping costs,
- replacement costs of operating components.

The reduced frequency of wastewater discharge is determined by equation 3 (Dobrzański and Galoch 2019).

$$Z = V_{sw} \cdot C_w \cdot \eta \quad \left[\frac{\text{PLN}}{\text{year}}\right] \tag{3}$$

where:

V_{sw} – volume of recovered water per year [m^3/year],
C_w – unit price of water and wastewater disposal from the tank, or unit price of water supply and wastewater disposal [PLN/m^3],
η – factor taking into account system efficiency [–],
$\eta = 1.0$ – reuse of grey wastewater and rainwater,
$\eta = 0.75$ – grey water,
$\eta = 0.9$ – reuse of rainwater.

The costs of water reuse systems for all three variants are shown in Table 1.

Analysis of the scenarios showed that reusing grey water and/or rainwater for toilet flushing and garden irrigation would save water up to more than 140 m^3/year. The amount of wastewater could be also reduced by 6 over the year. The price for water supply and wastewater disposal is also an important aspect. Each city has its own defined tariff. A low price for water causes a long period of return on investment. Therefore, a reduction of the cost of water and wastewater does not motivate the use of water reuse solutions, resulting in increased water consumption (Dobrzański and Galoch 2019).

Table 1

Costs of water reuse systems (Dobrzański and Galoch 2019)

System costs	Grey water and rainwater reuse system	Grey water reuse system	Rainwater reuse system
	Net price [PLN]		
Grey water reuse system	12,062.75	12,062.75	–
Rainwater reuse system	7,686.00	–	7,686.00
Control unit	3,112.83	3,112.83	3,112.83
Installation assembly	1,800.00	1,500.00	1,500.00
Total	24,661.58	16,675.58	12,298.83
Exploiting, PLN/year	595.00	595.00	25.00

Economic analysis of the grey water utilisation system

Stec and Kordana (2014) conducted an economic analysis of the grey water reuse. The study was conducted in Rzeszow, Subcarpathian province (Poland), for a single-family building, inhabited by 4 people. The building has a shower, 2 sinks, 2 toilet bowls, a washing machine, and a sink. The analysis presented the possibility of saving water by using a grey water management system. The treated grey water was to be used for flushing toilets and irrigating gardens in spring and summer. It is assumed that a total of 180 dm^3/day of wastewater from showers and sinks flows into the tank where the filter was installed. Washing machine wastewater was not considered a potential source of water for the buildings analysed, as it contains phosphates and can adversely affect garden vegetation. The reservoir provided 152 dm^3/day of treated grey water throughout the year, with the surplus discharged into the sewer system during the fall and winter. For the rest of the year, excess grey water and rainwater runoff from the roof was used to irrigate the garden (Stec and Kordana 2014). The analysis of scenarios is presented in Figure 7.

Each scenario took into account the capital costs of the internal water and wastewater system – PLN 8k. (kilo – one thousand). In addition, Scenario 1 included costs in capital expenditures related to the installation of a wastewater heat recovery system – PLN 3.5k. Scenario 2 included costs in the installation of a grey water utilisation system – PLN 14.5k. Meanwhile, in scenario 3, the additional costs relate to the system for economic use of rainwater – PLN 11k. Scenario 4 included costs from the purchase and implementation of a system combining the use of rainwater and grey water - PLN 16,760k., as well as the cost of heat recovery. Operating costs for the purchase of tap water and gas for Domestic Hot Water (DHW) heating were included for each scenario. Scenarios 2, 3, 4, additionally included the cost of pumping transport of water to the building's sanitary system. Scenarios 2 and 4 also included the cost of replacing the filter – PLN 2.5k. (Stec and Kordana 2014). The cost of LCCA for each scenario are shown in Figure 8.

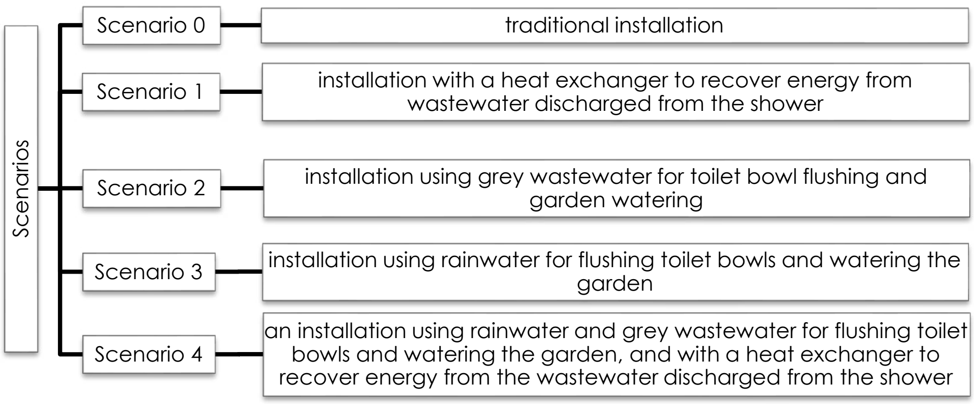

Fig. 7. Scenarios analyzed (Stec and Kordana 2014)

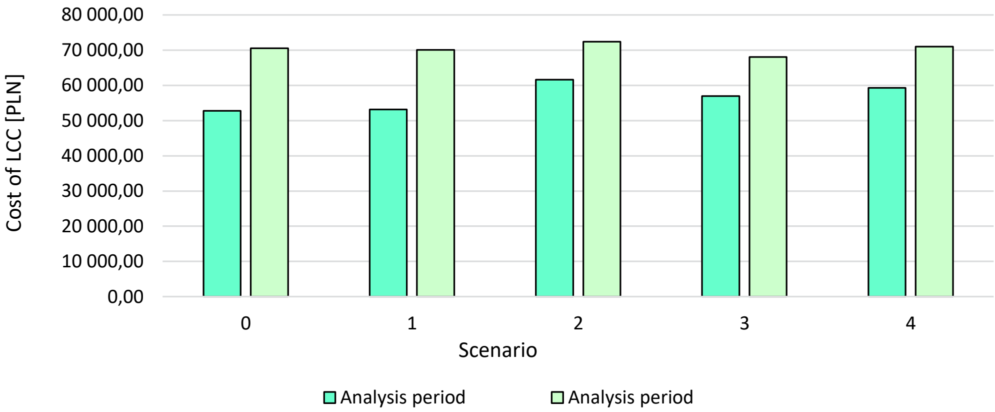

Fig. 8. Cost of Life Cycle Cost for analysed scenarios (Stec and Kordana 2014)

For a period of 15 years, the lowest LCC were obtained in Scenario 0. However, for a period of 20 years, the largest cash outlays will be allocated to cover the costs of Scenarios 2 and 4. Based on the analysis, it was alleged that the longer the analysis period, the cost-effectiveness of using scenario systems 1, 2, 3, 4 in relation to the scenario system with traditional installation increased.

2.2.3. Social assessment of water reuse

In the literature, data on social LCA related to water reuse are limited (compared to LCA and LCCA), due to the fact that this method is constantly evolving. In the literature, stakeholders attitudes to water reuse were analysed and an inventory was made in the field of water reuse.

The previous studies mainly covered the behavior of society towards water re-use processes. The main focus was on the factors that can influence public response. Smith et al. (2018) conducted research was conducted in demographic terms. It has been shown that these behaviors are related to age, sex, religious and ethnic groups, income and education (Smith et al. 2018).

Hartley (2006) research covered ten factors influencing public acceptance of water reuse. Acceptance is higher when:

- degree of human contact is minimal,
- protection of public health is clear,
- protection of the environment is a clear benefit of the reuse,
- promotion of water conservation is a clear benefit of the reuse,
- cost of treatment and distribution technologies and systems is reasonable,
- perception of waste water as the source of reclaimed water is minimal,
- awareness of water supply problems in the community is high,
- role of reclaimed water in overall water supply scheme is clear,
- perception of the quality of reclaimed water is high,
- confidence in local management of public utilities and technologies is high.

Currently, public access to drinking water is one of the most important topics. Circular economy in the water and wastewater sector strives for sustainable water consumption per person. It also includes the behavior of people in their households, their condition, and the improvement of knowledge. CE solutions can have a positive impact on environmental and social aspects, thanks to the introduction of, for example, green job places. The CE monitoring framework for water and wastewater management, including social aspects, is presented in Table 2 (Smol 2023).

Table 2

Social aspects in the CE Monitoring Framework for Water and Wastewater Management (Smol 2023)

Elements of CE Monitoring	Social aspects
Reduction	Water consumption per person Household water-saving activities
Reclamation (removal)	Access to clean water Access to toxic-free food from the aquatic environment Exposure to pollutants from the aquatic environment
Reuse	Access to recirculated wastewater
Recycling	Access to recirculated water
Recovery	Access to recovered energy Access to recovered raw materials (incl. nutrients)
Rethink	Increasing ecological awareness in the field of water and wastewater management Changing consumer behavior

Based on the research, it was found that one of the most important factors is to make stakeholders aware that properly treated and reused water is safe for health and life. People should be motivated to act in the field of reusing water from precipitation or grey water. Organisations that promote water reuse must engage in public participation to build public trust (Hartley 2006).

Conclusions

Currently, the problem of water shortage affects many countries of the world, including EU member states. As part of the protection of water resources, many organisations strive to reuse and recycle water, using traditional and innovative methods of water reuse. In recent years, the methods of water reuse in the water and wastewater management sector (grey water, municipal wastewater) and the reuse of rainwater have been successively developed. Thanks to the use of appropriate purification methods, water can be used for economic and agricultural purposes, as well as become a source of drinking water. When applying these methods, special attention should be paid to environmental, economic and social aspects. From the environmental point of view, water reuse reduces the drawing of water from primary sources. In terms of economic assessment, water reclaimed is more costly than abstraction from primary sources because it takes into account both installation and operating costs. Social evaluation is also important, which currently focuses mainly on the analysis of consumer attitudes and opinions. Methods of analysis of installations and methods of water recovery from various sources are developing, and water recovery practices themselves comply with CE.

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Iceland
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Management and use of by-products from coffee bean processing

Abstract: The generation of waste is inherent in any industry. Coffee is a popular commodity sold on the world market, which translates into the fact that the coffee industry contributes to the generation of very large amounts of waste at each production stage. The amount of waste generated in the coffee industry and its chemical composition and properties depend on the coffee processing technology used. The high amount of waste negatively affects the environment. This prompted researchers to develop a sustainable management plan and procedures for handling the generated waste. Currently, waste from coffee bean processing finds applications as a valuable resource for composting, as a source of energy, and also in the chemical industry as a biosorbent. Despite many explored possibilities for the reuse of solid waste from coffee bean processing, research in this direction should continue. This is due to the immense potential of the identified solid waste as a source of renewable resources, as well as the increasing opportunities for studying this issue.

Keywords: circular economy; environmental sustainability; coffee waste; raw materials

Introduction

The term "coffee" refers to the beans and fruits of the coffee bush classified in the genus Coffea, the family Rubiaceae and the subclass Asteridae (Dmowski and Polewko 2017). However, the term also refers to a hot brew prepared from processed coffee beans. According to current reports, an average of 1–2 cups of coffee per day are consumed in Poland. In addition, about 66% of Poles said they regularly consume coffee every day (Surma et al. 2023). Coffee is a widespread commercial commodity both in the Polish and global markets, and the demand for it is constantly growing. The most common coffee species in the world include Coffea arabica (Arabica), Coffea canephora (Robusta) and Coffea liberica (Liberika) (Clarke 1989). The largest coffee plantations are in Brazil, Peru, Mexico, Colombia (about 60% of the global cultivated area) and Africa – mainly in Ethiopia (about 30% of the area) (Dmowski and Polewko 2017). According to a report by the International Coffee Organization (ICO), it is estimated that coffee tree is grown in at least 50 countries worldwide (ICO 2019). The coffee supply chain is very complex, on the way to the consumer from farmer's coffee beans change owners several times. Figure 1 shows the global coffee value chain (ICO 2020).

Coffee beans have an extremely complex chemical composition, depending, for example, on the way the coffee plant is grown, the location of the coffee plantation, optimal environmental conditions, the method of cleaning the beans, as well as the degree of roasting (Dąbrowska-Molenda et al. 2019). The major chemicals detected in coffee beans are tannin, caffeine, thiamin, citric acid, spermidine, xanthine, guaiacol, chlorogenic acid, spermine, acetaldehyde, scopoletin, putrescine. In addition, coffee beans have wax and oil (Sharma 2020; Mussatto et al. 2011). Coffee beans have also biologically active substances, vitamins and minerals (Matysek-Nawrocka and Cyrankiewicz 2016; Nieber 2017; O'Keefe et al. 2018).

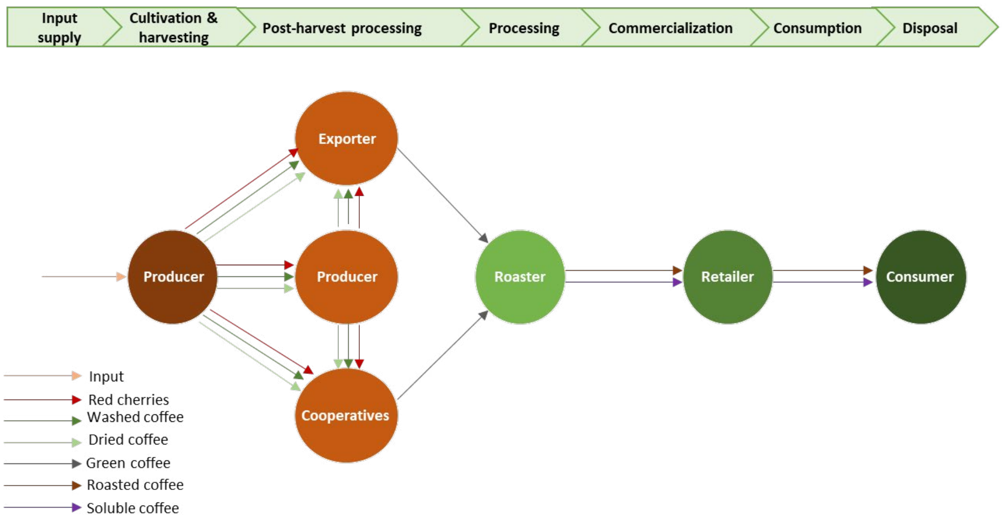

Fig. 1. Coffee global value chain. Own compilation based on literature data (ICO 2020)

Coffee is one of the most important commercial commodities on the world market, which consequently generates very large amounts of waste during the processing of coffee beans (Clarke 1989). It is estimated that global coffee production has increased by more than 60% since the 90s. The annual value of coffee exports is USD 35.6 billion in 2018 (ICO 2020). According to these data, the forecast total production in the 2021/2022 coffee year is 167.2 thousand 60 kg bags, which indicates a decrease of 2.1% compared to 170.83 thousand 60 kg bags in the previous coffee year. It is estimated that global coffee consumption will increase to 170.3 thousand 60 kg bags in 2021/2022 compared to 164.9 thousand 60 kg bags in the 2020/2021 coffee year. In 2021/2022, consumption is predicted to exceed production by 3.1 thousand 60 kg bags (ICO 2022).

Coffee bean processing technology has undergone constant modifications over the turn of the century, which translates into changes in the amount and type of waste obtained (Vincent 1987). With the aspect of a circular economy, waste from coffee processing can be a high-value raw material in alternative industries (Lewin et al. 2004; Andrzejuk 2016). Hence, the purpose of the presented article is to review the literature related to the sustainable management of waste from the coffee bean processing industry.

1. Coffee processing technologies

Existing coffee fruit processing technologies are used to clean and pulverize raw coffee beans from the husk and pulp before roasting. Three coffee processing technologies can be distinguished – dry, wet and semi-dry (Vincent 1987). The dry method is the earliest method of processing coffee. The name of the method comes from the fact that the dry method doesn't use water. Whole coffee cherries are dried on separate tables (30 days). The dried coffee cherries go into hulling machines. Finally, the coffee beans are segregated and sorted. This is a cheap, simple method that doesn't need complicated equipment or a lot of energy. The method is slow, requiring a lot of drying area and regular mixing to avoid fermentation and mold on the tables (Nursten 1982; Vincent 1987). Drying coffee cherries can be done "artificially" or "naturally" (Vincent 1987). The wet method needs expensive, specialized processing equipment and a lot of clean water. Without the outer husks, the coffee beans go into fermentation tanks for about 24 hours. After this time, they are dried. Finally, the coffee beans are selected. Defective coffee beans are disposed of as waste (Vincent 1987). The main stages of wet coffee processing are shown in Figure 2. The semi-dry method is the latest coffee processing method. This method is a mix of dry and wet coffee processing. First, the pulpy part of the coffee fruit is removed and the coffee beans are left exposed. The coffee beans are dried (Vilela et al. 2010).

The generation of waste is inherent in any industry. Coffee is a popular commodity sold on the world market, which translates into the fact that the coffee industry contributes to the generation of very large amounts of waste at each production stage (Nabais et al. 2008). Depending on the coffee processing technology used (dry, semi-dry, wet), waste is generated with different organoleptic properties, chemical composition, taste and aroma. Also depending on the technology used depends on the amount of solid waste generated. In addition, during these processes several stages also generate large amounts of wastewater. After initial processing, green coffee is subjected to the roasting process, which can almost totally change its physicochemi-

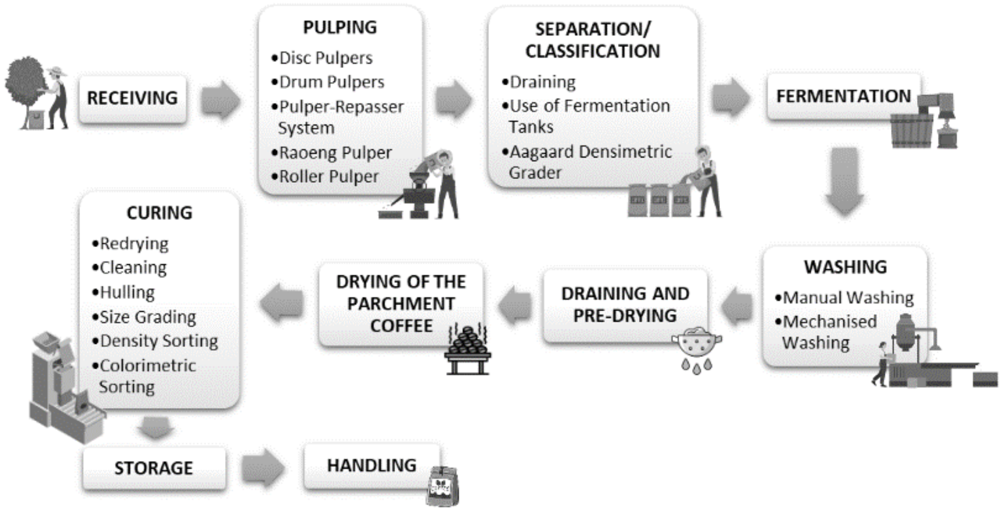

Fig. 2. The main steps of the wet coffee processing method. Own compilation based on literature data (Vincent 1987)

cal composition, and consequently also the resulting waste. Waste is also generated directly after the coffee beans are roasted and after the beverage is prepared (Cruz 2014). Waste from coffee bean processing and its main components are listed in Table 1.

Table 1

Coffee processing waste and its main components. Own elaboration based on literature data (Sisti et al. 2021)

Coffee waste	Coffee pulp from wet processing of coffee fruit	Coffee silver skin from the roasting process	Coffee husk from dry processing of coffee fruit	Spent coffee ground from coffee brewing
Main composition	carbohydrates, proteins, minerals, tannins, polyphenols, caffeine	fibers, proteins, polyphenols	carbohydrates, proteins, moisture, ash, lipids	sugars, proteins

This prompts companies to engage other industries to develop a plan for the sustainable management and handling of the resulting waste by current national regulations. Nowadays, there are a growing number of specialized industries involved in the collection and management of coffee processing waste, including its sale for various purposes, i.e. composting, raw material for biofuel production, mushroom cultivation (Pujol et al. 2013).

2. Sustainable management of coffee processing waste

In recent years, public awareness of issues such as environmental pollution and shortages of many raw materials used in various industries has increased. This has contributed to an increased search for new, innovative and environmentally friendly methods of managing the waste generated. The possibility of reusing waste is an extremely important issue from the point of view of the circular economy (Sisti et al. 2021). Due to the numerous problems occurring on a global scale, today's society is increasingly inclined towards the circular economy and the so-called green deal. The main premise of the circular economy is to minimize the consumption of natural resources and minimize the production of waste. According to the EU, the idea of the circular economy is to allow it to meet its environmental goals (Jaworski and Grochowska 2017).

According to current reports, it is expected that up to 100 million tons of food waste are produced in the EU each year. Unfortunately, such a large amount of waste has a negative effect on the ecosystem and can consequently negatively affect people's quality of life and health. It is predicted that the amount of waste generated could more than double by 2050. This prompts further research to determine the potential of waste generated in the food industry and agriculture as a source of renewable raw materials. Such future research will allow sustainable management of the waste generated (ICO 2022).

The popularity of coffee in the global market has contributed to the coffee industry is responsible for generating huge amounts of waste from the very first step (Nabais et al. 2008; Toschi et al. 2014). It is estimated that more than 23 million tons of coffee processing waste are generated annually. The amount and chemical composition of coffee processing waste vary depending on the technology used, among other factors. As mentioned in Table 1., the main solid wastes generated in large quantities include spent coffee grounds, coffee husks, coffee pulp, coffee silver skin and defective coffee beans. According to the available literature on the subject, the aforementioned coffee processing wastes show high potential for producing valuable materials and extracting valuable raw materials, as described later in this article (Bonilla-Hermosa 2014; Janissen and Huynh 2018).

2.1. Coffee processing waste as raw material for composting and vermicomposting

The processing of agricultural products results in the generation of huge amounts of agro-industrial waste. Commonly, to get rid of such waste, it is burned or animal feed is produced. However, this is not cost-effective and beneficial to the environment and the animals that live there. The rich chemical composition of agro-industrial waste indicates its potential as a raw material for production, in addition, its reuse can reduce production costs. The problem is that such agro-industrial waste may contain compounds of a toxic nature (e.g. phenols), which do not allow the waste to be used for animal feed. Hence, recycling agri-food waste can bring not only environmental benefits but also economic benefits (Matos 2008).

One of the most cost-effective and environmentally beneficial methods of managing agri-food waste is composting and vermicomposting. Agri-food waste can be recycled in this way on an industrial scale. Waste processed in this way improves the quality and nutrient composition of the soil, allows for better-quality crops and has commercial value (Murthy and Naidu 2012). Among agri-food waste, a large percentage is a waste generated during coffee processing. This is because coffee is one of the largest commercial commodities worldwide. Special attention must be paid to coffee husks and pulp among coffee processing wastes. This is because of their rich chemical composition. They are rich, especially in potassium and other mineral nutrients. Their rich chemical composition has prompted a great deal of research into their possible use (Matos 2008). Coffee husks and coffee pulp are very good raw materials for composting and vermicomposting. Although coffee pulp has more cellulose than potassium and lignin, it has great potential for moisture retention. The solid parts of coffee pulp prove to be a very good source of organic carbon and humus. The disadvantage of using the coffee pulp in composting and vermicomposting is its slow decomposition. When coffee pulp is turned over in heaps every few days this waste will be composted within 3 weeks. The use of this agri-food waste has a beneficial effect on soil fertility and also stimulates plant growth. The solid waste generated during the production of instant coffee is a rich source of organic compounds. Therefore, numerous studies are being conducted on their potential. Research using forced aeration in the composting process of solid waste generated during the production of instant coffee has led to the production of very high-quality compost. In this way, more than 87 thousand tons of high-quality organic fertilizer were produced from about 350 thousand tons of coffee pulp. Such organic fertilizer is used, among others, in coffee nurseries, gardens, when growing other plants, etc. (Murthy and Naidu 2012). In addition to coffee husks and coffee pulp, in some countries, due to its rich chemical composition, coffee silver skin from coffee not subjected to any preliminary physicochemical treatment is used as a raw material for the production of high-quality organic fertilizers (Saenger et al. 2001). Coffee pulp is a source of nutrients. That's why coffee pulp is used as a raw material to produce organic fertilizer. Such organic fertilizer improves soil properties and enriches crop yields as indicated by numerous scientific studies. It is important that the use of natural organic fertilizers greatly reduces environmental pollution and saves a lot of money by farmers. In addition, the use of natural organic fertilizers reduces the production and use of artificial inorganic fertilizers (Padmapriya et al. 2013). Dadi et al. (2019) in their work indicated the potential for composting and co-composting coffee pulp and husks with source-separated municipal waste. The results indicate that both peelings and coffee pulp can be co-composted with municipal waste as well as composted on their own. In this way, stable compost can be obtained.

Also, great potential is shown by used coffee grounds, which are suitable for composting due to their rich chemical composition and the biologically active compounds present. Nowadays, a lot of natural fertilizers are being produced using used coffee grounds (Andrade et al. 2022). In the experiments of Kassa et al. (2011), the properties of compost using coffee-processing waste were evaluated, the physical and chemical parameters of which changed with the composting process. The results showed that composting with coffee-processing waste makes it possible to obtain quality compost. In addition, it was noted that it is better to supplement coffee processing waste with other organic materials before composting to improve the quality of the resulting compost. Murawska (2020) in her work demonstrated the possibility of using used coffee grounds as a composting supplement to improve the quality of the resulting compost. Data obtained by Adi et al. (2009) indicate the potential of coffee grounds in the vermicomposting process. Adding coffee grounds helps improve the quality of the resulting vermicompost.

2.2. Coffee processing waste as an energy resource

From the point of view of the current global situation, energy production from waste and renewable materials is a very attractive alternative to traditional energy production methods. Spent coffee grounds are produced in rigorous quantities annually, hence, thanks to numerous studies on their potential as a raw material for energy production, this idea can be used on a larger scale. Nowadays, used coffee grounds may be used as fuel in commercial boilers because of their high fuel value – 5000 kcal/kg. The calorific value of used coffee grounds is comparable to other used agri-food waste (Murthy and Naidu 2012). Kondamudi et al. (2008) undertook a study on the extraction of oil from used coffee grounds and its further conversion to biodiesel. Depending on the grade of coffee used (Arabica or Robusta), about 10–15% oil was obtained. The experiment proved that the biodiesel obtained from spent coffee grounds was stable for about 1 month. The same authors pointed out the potential for producing fuel pellets and ethanol using spent coffee grounds. Oliveira et al. (2008) experimented to test the feasibility of biodiesel production using oil extracted from healthy and damaged coffee beans. The results showed the potential of coffee oil for biodiesel production from both defective and healthy beans, which is because the respective oils were successfully converted into fatty acid methyl and ethyl esters. However, for coffee oil-based biodiesel production to be a fully environmentally friendly production, it is necessary to consider alternative ways of managing the solid waste generated. One suggestion was indicated by Nunes et al. (2009) in their work, where they investigated the possible potential of the resulting solid waste as a feedstock for the production of alternative activated carbon. Figure 3 shows the process of producing biodiesel and fuel pellets using spent coffee grounds. Currently, only a small amount of coffee parchment grounds is used for energy purposes, mainly to produce fuel for drying coffee beans and as an energy source for masonry processes.

This is mainly because there is not enough information on the combustion and emission characteristics of this waste. Available literature suggests that in some countries, coffee silver skin from coffee has the potential to be used in fuel production (Saenger et al. 2001). Dadi et al. (2018) experimented to test the feasibility of producing bioethanol from different fractions of coffee waste using hydrolysis while confirming the potential of coffee processing waste.

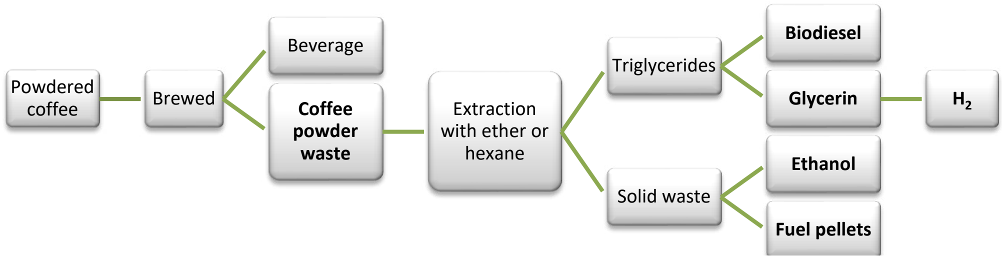

Fig. 3. A general schematic showing the process of producing bioenergy from used coffee grounds. Own compilation based on literature data (Kondamudi et al. 2008)

Figure 4 shows some of the better-studied examples of coffee waste valorization in bioenergy production. The technologies used to produce bioenergy are listed, as well as what secondary products are produced during the process.

Coffee Waste	Methods	Secondary Products	Fuel
Spent coffee grounds	Pyrolysis	Biochar/Syngas	Bio-oil
Spent coffee grounds	Hydrolysis/Fermentation	Fuel pellets	Bioethanol
Spent coffee grounds oil	Chemical/Enzymatic conversion	Glycerin to bio-hydrogen	Biodiesel
Spent coffee grounds oil	Enzymatic conversion	Glycerin to bio-hydrogen	Biodiesel
Defatted spent coffee grounds	Hydrolysis/Fermentation	Fuel pellets	Bioethanol
Defatted spent coffee grounds	Pyrolysis	Biochar	Bio-oil

Fig. 4. Examples of valorization of coffee processing waste in bioenergy production. Own compilation based on literature data (Sisti et al. 2021)

2.3. Coffee processing waste as biosorbents

As a result of industrial development and various human activities, a huge amount of pollution enters the ecosystem. Among the most dangerous pollutants of anthropological origin for the environment are pharmaceuticals and heavy metals. Both of the aforementioned pollutants are characterized by their high ability to accumulate in the environment, in the organisms and plants that live there. An additional threat is their low biodegradability. As a result, the concentration of these pollutants is significantly increased, which can carry further adverse environmental effects. Both pharmaceuticals and heavy metals are detected in large quantities in soil and water, but it has been shown that they can escape into the atmosphere, where they can react with dust particles to create another threat to the environment and human health (Kim and Kim 2020; Skorupa et al. 2023).

Hence, new and effective methods are constantly being sought to eliminate or reduce the aforementioned pollutants of anthropological origin. There are several methods to reduce these pollutants, but they are costly and can contribute to the creation of waste, which can be toxic. Currently, adsorption on adsorbents is considered the most favorable method for reducing contaminants. It is a simple, relatively inexpensive and effective method of eliminating contaminants such as heavy metals, pharmaceuticals. Currently, the most commonly used material serving as an adsorbent is activated carbon (Minamisawa et al. 2004; Zuorro and Lavecchia 2010; Kim and Kim 2020). However, the production of activated carbons made from materials like wood or lignite is expensive, so alternative, low-cost and readily available adsorbent materials are constantly being sought (Babel and Kurniawan 2003; Xu et al. 2019). Demirbas (2008) noted that low-cost, high-efficiency adsorbents can be produced using waste from the agri-food sector, such as coffee waste (skin, spent beans, pulp) to reduce anthropic pollution from the environment.

Coffee grounds are considered the main waste from the coffee industry, accounting for the largest portion of the waste generated. There is still insufficient research on the potential of spent coffee grounds as a raw material for the production of adsorbents for the reduction of anthropic pollutants from the environment. On the other hand, there are studies indicating that heavy metals can be reduced by adsorption through complexation using spent coffee grounds. This is due to the small size of coffee grounds, high specific surface area, high porosity and chemical composition (McNutt and He 2019; Azmi et al. 2022).

Spent coffee grounds also show great potential for reducing other contaminants such as pharmaceuticals, pesticides and various organic compounds. Zungu et al. (2022) conducted an experiment using created biocarbon from used coffee grounds through a pyrolysis process and investigated its potential to reduce pharmaceuticals from the aquatic environment. The results of the experiment confirmed the potential of the created biocarbon to reduce pharmaceuticals that pollute the aquatic environment.

2.4.Other ways of managing coffee processing waste

In addition to the previously described methods of managing coffee processing waste, there are many cost-effective and environmentally friendly ways to manage it. Many factors influence the rational management of this waste. The use of environmentally beneficial methods of disposing of coffee processing waste requires an understanding of its chemical composition, its potential uses, possible processing methods and recycling. For example, coffee husks and coffee pulp, due to their chemical composition, have found use mainly as an additive for composting and vermicomposting, as a raw material for the production of high-quality fertilizers and animal feed. However, despite the widespread use of this waste, a large part of them is still not managed. Therefore, further research is being undertaken into their potential use. Attempts are being made to detoxify these coffee wastes to obtain safer and higher-quality animal feeds and to obtain various types of products, such as enzymes, aroma and flavor compounds, organic acids or additives for mushroom breeding (Murthy and Naidu 2012).

The nutrient-rich coffee pulp can be a valuable raw material for animal feed. Unfortunately, it carries a rather limited value. This is because the cost of drying the pulp is often higher than the profit, and it is not worth doing. In addition, there is little information on the effects on animal health of substances such as tannins, caffeine or large amounts of potassium (Padmapriya et al. 2013). Goiri et al. (2020) indicate the potential of spent coffee grounds as an element in ruminant diets due to their antioxidant and antibacterial characteristics.

Due to the high amount of sugars and rich chemical composition, such coffee wastes as coffee husks and coffee grounds are suitable for the production of special growth media used in yeast and mold breeding. For the production of such growth media for the cultivation of edible mushrooms, coffee waste not subjected to any preliminary physical and chemical treatment is used. Coffee husks are also treated as a cheap substrate for the production of citric acid by A.niger during solid-state fermentation. In addition, gibberellic acid can be produced using coffee husks, as this waste provides a source of carbon. Gibberellic acid production reached 1100 mg/kg when dry coffee husks were used as the only fermentation substrate (Murthy and Naidu 2012).

It is currently estimated that coffee husks and coffee pulp show potential as a substrate in bioprocesses. The most common pads have been conducted confirming their positive use in the production of aromatic compounds and enzymes. Using coffee husks and coffee pulp, enzymes such as caffeinase, amylase, tanninase, pectinase, protease and xylanase are most commonly produced. Battestin and Macedo (2007) showed an 8.6-fold increase in tannin enzyme production when using coffee skins from P.variotii under optimal conditions. For the synthesis of fructooligosaccharides and β-fructofuranosidase by A.japonicus during solid-state fermentation, coffee silver skin is used, which has great potential as a source of vital nutrients. The chemical composition of coffee silver skin and spent coffee grounds indicate the potential for using these coffee wastes in the production of various value-added compounds (Murthy and Naidu 2012).

An interesting way to use spent coffee grounds is to use them like an insect deterrent (Andrade et al. 2022). It is worth noting that the synthetic herbicides commonly used to eliminate weeds are not environmentally friendly and contribute to environmental pollution. This may result in future human health problems. Therefore, the search for alternative, efficient and environmentally friendly natural herbicides are being pursued. Such a concept is conducive to the idea of the circular economy. Lorenzo et al. (2022) showed that used coffee grounds had the potential to control weeds in the field in some parts while having no negative impact on other plants. The results of the study were influenced by varying environmental conditions. However, the possibility of using spent coffee grounds as a potential bioherbicide was recognized. Figure 5. shows the potential uses of spent coffee grounds.

Coffee silver skin, due to its rich chemical composition, is also used as an additive in anti-aging products and as a functional dietary additive (Mussatto and Teixeira 2010; Mussatto et al. 2012; Bilbao et al. 2014). Procentese et al. (2018) pointed out the possibility of using coffee silver skin as a raw material for the production of solvents in fermentation processes. Unfortunately, there are few studies on the production of biocarbon from such coffee wastes as spent coffee grounds and coffee parchment. However, those that are published indicate the ability of such biocarbon to immobilize heavy metals in contaminated soil (Carnier et al. 2022).

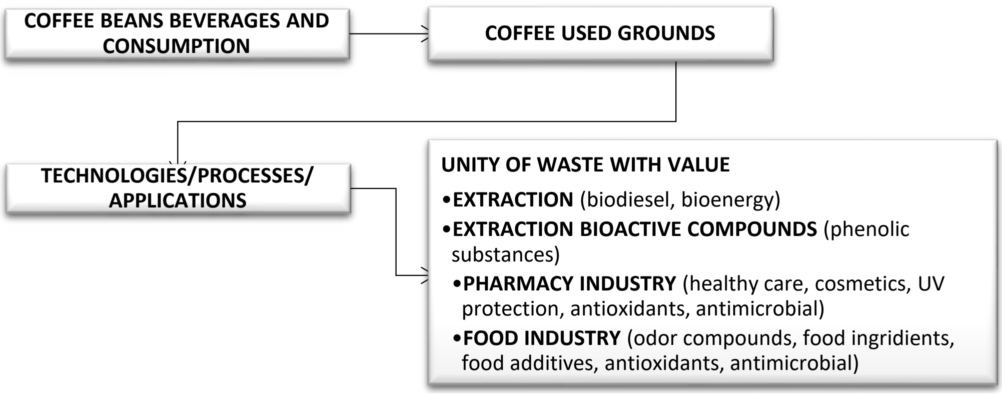

Fig. 5. Common examples of potential management of used coffee grounds. Own elaboration based on literature data (Andrade et al. 2022; Skorupa et al. 2023)

Conclusions

Based on the above, the following conclusions were formulated:

- A large amount of solid waste from the food and agricultural industries has a negative impact on the ecosystem, and consequently, it can adversely affect the quality of life and human health. It is predicted that the amount of waste generated could more than double by 2050. This prompts further research to determine the potential of waste generated in the food industry and agriculture as a source of renewable raw materials. Such future research will allow sustainable management of the waste generated.

- The coffee industry generates a huge amount of waste - more than 23 million tons per year. This large amount of waste negatively affects the ecosystem. This prompts further research to determine the potential of waste generated from the food and agriculture industry not only in terms of disposal but also as a source of renewable raw materials.
- The possibility of reusing waste is an extremely important issue from the point of view of a circular economy, in line with the European Green Deal.
- According to the literature, coffee waste shows great potential for producing high-value materials and extracting valuable biologically active substances.
- However, despite the many cost-effective and environmentally friendly ways to manage coffee waste, further research should be conducted in this sphere, as there are still many gaps in the available knowledge that limit the possibilities of using coffee waste on an industrial scale.

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