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Sustainability of water supply management for Erbil City in the context of sustainable development agenda

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A R T I C L E I N F O

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A B S T R A C T

Conserving water and providing for the future generation is one of the most important principals established on the agenda concerning sustainable development goals. The aim of the paper is to evaluate the sustainability of the quantity and quality of water sources for Erbil City, as well as their safety and security based on the standard limitations. Therefore, the study computed the adapted scale of measuring water quantity and the demand of water and then evaluated the collected data from the water directorates related to both surface water and groundwater for the studied area. The study focused on the management of water supply and main factors that affected the lack of the sustainability. The next step was the planning of appropriate solution for those problems, such as avoiding drilling of illegal groundwater wells and managing water sector that made the poor water management as well. The use of additional surface water accomplished with the construction of extra water treatment plants was seen as an alternative to consuming groundwater. Reusing of processed sewage for various consumption and recharging of groundwater was considered as sustainable strategy and management for the water field in Erbil City.

1. Introduction

In general, surface and groundwater have a crucial role in water supply system, and it is used for irrigation purposes as well. Recently, Erbil City, which is in the northern part of Iraq that is considered to be rapidly expanding area due to increasing population number, faced the economic problems. However, it is necessary to monitor and better manage the sources of water and provide water for following years (Mustafa et al., 2021). The impact of climate change and sustainability of both groundwater and surface water resource is important. The requirement for groundwater studies are necessary for sustainable management of water resources and it is also important for considering the climate change and it's variability for a long periods in order to better manage the underground system that has increased due to the required demand (Nanekely et al., 2017; Mustafa et al., 2021). However, groundwater is a vital source for agricultural, domestic, and industrial purposes in almost every country. The demand for water increases due to population growth, therefore the problems concerning groundwater sources should be taken into account (Hawez et al., 2020). Meanwhile, the water demand in Erbil City has also increased due to population growth. In addition, the percentage of domestic wells represent 40 % of water supply system in the city (Wali and Alwan, 2016). Mostly, Erbil City uses groundwater for irrigation,

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industrial, and other daily activities (Wali and Alwan, 2016). Moreover, the groundwater quality depends on the composition of the aquifer recharge and interactions between both material and the groundwater. It is obvious that clean water is used for many activities based on WHO recommendation which states that about 80 % of all the diseases in human beings are caused by water (Toma et al., 2013; Mustafa et al., 2021).

There are numerous studies on the sustainability of the water resources. Halim et al. (2010) studied the causes of spreading disease through water among people, factors affecting the sustainability of water resources, are the increase in population and the climate change pressure. Vishwajit and Sumit (2012) did the investigation on sustainability of sources, and the study conducted by Toma et al. (2013) was on groundwater quality in Erbil City. Jadoon et al. (2015) studied water quality in Erbil City, also the article of Ahmed and Miran (2016) explained the sustainability for water sources in Erbil City. Moreover, Bapper and Younis (2016) evaluated the water quality in Erbil City as well.

On the other hand, there is also the study of Dizayee (2018) on groundwater level in Erbil Basin, and Qurtas (2018) determined the recharge of Erbil groundwater. Mawlood and Omer (2019) used Kriging Method to estimate the depth of the Erbil groundwater. Later, Mawlood (2019) did the investigation on groundwater sustainability for the studied area. Mahmood and Omar (2019) studied the amount of water supplied for population of the selected area. Then, Hawez, et al. (2020) published the study on quality of the groundwater for the cities in the Kurdistan Region Governorate. The presented study tried to evaluate the problems in water resources management in the future, and also determine the basic plan to face the water sector problems. The major problem was lowering groundwater table due to numerous illegal wells, and then developing the projected sources of surface water for better management of water resources. Water demand for domestic uses has reached more than (320,000 m^3/day), while, the demand for agricultural and industrial uses in the city has not been computed yet (Shekha, 2008). Furthermore, Shareef and Muhamad (2008) reviewed a number of studies on water quality in Erbil Governorate. Al-Ansari (2013) studied water resources development in Koya City. In another research, Hameed (2013) studied water harvesting for Erbil Governorate by using geographic information system (GIS) and remote sensing. Saeedrashed and Guven (2013) estimated the geomorphologic parameters by using GIS for Lower Zab River-Basin. In addition, Mawlood and Hussein (2016) discussed water management system for Mala Omer in Erbil City. Tinti (2017) studied water resources management for Kurdistan Region of Iraq. According to Dizayee (2018), there were many illegal wells in the central sub-basin of Erbil. Al-Kubaisi et al. (2019) described water balance for the central basin of Erbil area. Additionally, Hiscock et al. (2002) stated that providing future sustainable groundwater development would need a common understanding of each individual based on information and education that promoted cooperation and responsibility of each person. Consequently, the objective of the present research was to assess the management and sustainability of the quantity and quality of water sources in Erbil City.

2. Materials and methods

2.1. Study Area Location

Erbil Province is the capital of Kurdistan Region of Iraq, and is located on the north-east of Iraq, which covers about 197 km^2 with the elevation of the 414 m above sea level (Mahmood and Omar 2019; Mustafa et al., 2021). It is surrounded at the north-west by the Greater Zab River and at the south-east by the Lesser Zab River. Boundaries extend from longitudinal 43°15¯ E to 45°14¯ E and from latitude 35°27¯ N to 37°24¯ N, Figure 1. Mainly, the sources of water in the city belong to two types, which are surface and groundwater sources. The Greater-Zab River is the chief surface water source for water supply in Erbil City (Aziz and Mustafa, 2019). Three water treatment-plants (named Ifraz 1, Ifraz 2, and Ifraz 3) exist on the Greater-Zab River, Figure 2. The other source is groundwater which supplies water throughout drilled wells for the consumers. This study is highly focused on the sustainability of the groundwater management for the selected area based on the provided data obtained from government organizations and previous investigations.

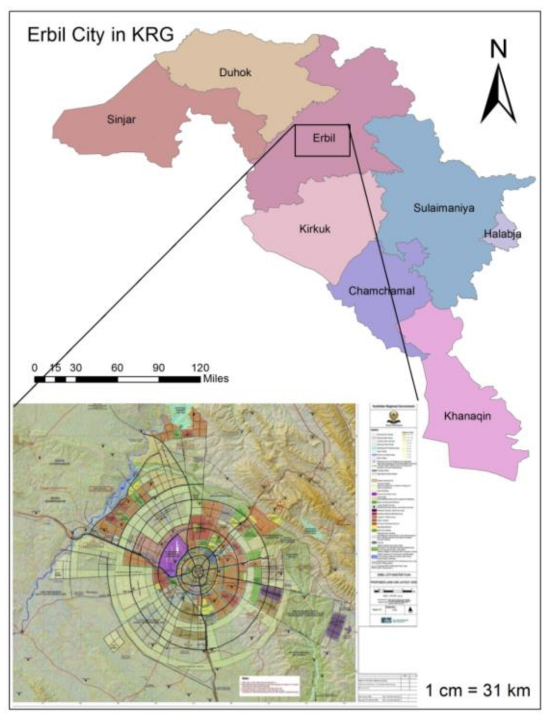

Figure 1. Study area location created by GIS (Arc Map 10.4)

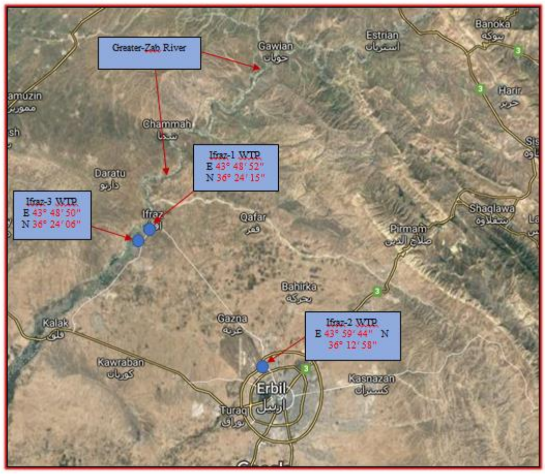

Figure 2. Location of water treatment plants on Greater-Zab River (Omar, 2020)

According to Al-Kubaisi, (2019), that the Erbil basin is a plain divided into three sub-basins, Kapran, the central basin which includes Erbil city, and Bash Tepa basin. It is also bounded on the Greater-Zab and Lesser-Zab Rivers from the northwest and southeast, respectively.

2.2. Water Supply Estimation (Quantity and Quality)

Generally, the estimation of the quantities of the water sources for Erbil City that depend on the groundwater from pumping of water in the wells was investigated. Omar (2020) reported that the amounts of drinking water for Erbil City during 2014 to 2018 were:

- (139,036,720) m^3/year (2014),
- (143,472,095) m^3/year (2015),
- (158,069,446) m^3/year (2016),
- (164,331,177) m^3/year (2017),
- (172,687,525) m^3/year (2018).

The presented data was obtained from the series of 60 sets of monitoring of the production wells, and it represented the average monthly amount of supplied water to the consumers in Erbil City. Therefore, the number of inhabitants obtained from the Central Statistical Office (CSO) was estimated at 1,365,000 with the annual calculated growth rate of 3.5 % (Mahmood and Omar, 2019).

On the other hand, the determination of water quality for the water sources in Erbil City was based on the previous studies. Aziz (2004) studied the seasonal variation of water and wastewater for the study area. The author obtained the samples from well No.3 in Iskan Quarter. Toma et al. (2013) investigated water quality for the six groundwater wells in various quarters (Ronaky 1, Tayrawa 1, Badawa 13, Azadi 8, Rizgari 1, and Ankawa 9) in Erbil City, and explained that the quality of water was suitable for drinking purposes. Ground water wells are illustrated in Figure 3.

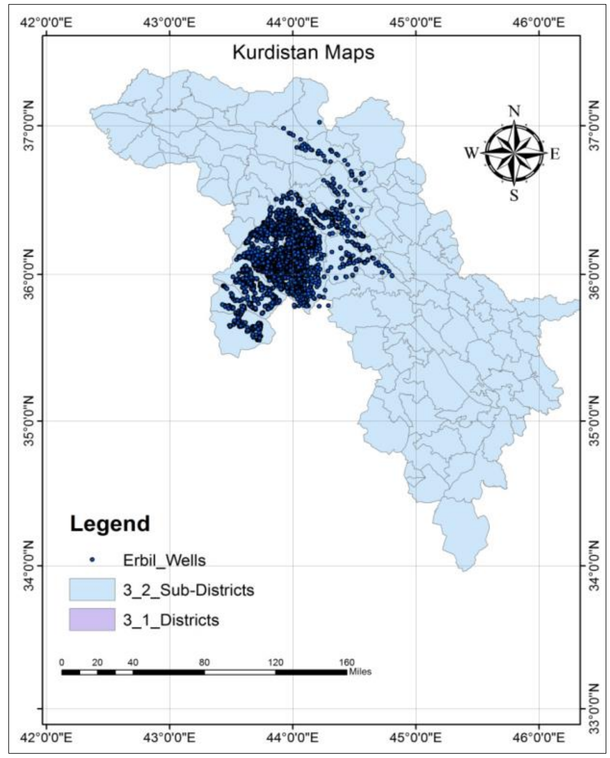

Figure 3. Groundwater wells in Erbil City

Moreover, the water quality for fifty groundwater wells within Erbil City were tested by Daham et al. (1998). In addition, the study observed a high pH, turbidity, total hardness, and alkalinity of water in Erbil City. Similarly, in both Bakhtiari and Ainkawa quarters, five groundwater wells tested by Jadoon et al. (2015). The authors reported that the water quality from a number of groundwater wells was subjected to contaminants such as high concentration nitrates and pathogens (Hawez et al., 2020; Mustafa et al., 2021).

2.3. Sustainability of the Water Resources Management

In general, there are a lot of points that should be considered. During this study, it is observed that the water management is very poor that may cause the depletion in groundwater table in the study area because there are a number of illegal wells without recording, Figure 3. In spite of this, the actual number of the drilled wells is higher than the recorded wells as it is pointed out by Dizayee (2018). Therefore, most of the drilled wells were dried and the people faced the draught problem in the area. Second point, about the surface water which directly converted water from the existence Ifraz Water Treatment Plants on Greater Zab River to Erbil City for water consumption purposes (Aziz and Mustafa, 2019). Table 1 illustrates the details of Ifraz 1, Ifraz 2, and Ifraz 3 Water Treatment Plants.

Groundwater is the main source of water for drinking and irrigation purposes, and it is also a unique resource,

Table 1
Detail of the Water Treatment Plants on Greater-Zab River (Omar, 2020)

No.	WTP	Constructed year	Location of distributions	Discharge (m^3/day)	Location of WTP
1	Ifraz 1	1968	Erbil city	34,000	Ifraz village
2	Ifraz 2	1983	Erbil city	44,000	Erbil city
3	Ifraz 3	2007	Erbil city	216,000	Ifraz village

widely available and providing security against droughts. It is linked to surface water resources and the hydrological cycle. Meanwhile, this source is reliable supply, uniform quality, temperature, relative turbidity, and pollution free, however, the minimal evaporation losses are attributed to making groundwater source more attractive when compared to other sources Menon (2007).

In the current study, the approximate quantity of groundwater water wells was calculated. The data for 1,100 wells were used (General Directorate of Water and Sewerage in Kurdistan Region-Iraq, 2020):

- The estimated rate of well drainage for each well = 25 m^3/hr.
- The average number of operating hours for each well = 15 hours
- The produced water from wells = 412,500 m^3/day.
- Total discharges for the Ifraz 1, Ifraz 2, and Ifraz 3 Water Treatment Plants is 294 m^3/day, Table 1.
- The total quantity of available water for Erbil City is approximately equal to 706,500 m^3/day.

The rate of losses is about (15 %) (General Directorate of Water and Sewerage in Kurdistan Region-Iraq, 2020). Thus, the remaining net quantity (85 %) is 600,525 m^3/day. Average daily water consumption in Erbil City is nearly 380 liters/person/day (General Directorate of Water and Sewerage in Kurdistan Region-Iraq, 2020; Mustafa et al., 2021).

2.4. Quality of Water

In general, polluted surface water source cannot be used for the purpose of drinking and daily consumption because it contains some pollutants that do not conform with the drinking water standards. Often the percentage of turbidity, suspended matter and bacteria in the surface water source is more than the permissible limit for drinking water. According to Iraqi Standards, the turbidity should be less than 5 NTU (Abbawi and Hussein, 1990). Previous studies showed that the turbidity is around 100 NTU, and during rainfall times more than 1,000 NTU (Omar, 2020). Therefore, surface water filtering through the filtering plants is necessary in order to reach a degree that matches the drinking water standards.

Hearing that the running water is clean, the percentage of dissolved oxygen increases with the circulation of the water waves, and it is possible that some materials settle at the bottom of the river, and the water can be used for irrigation, for fish farming and for construction in general, but the problem of bacteria and rust remains and the water needs to be filtered and sterilized for the purpose of its use for drinking and household consumption (Aziz, 2006; Davis and Cornwell, 2008; Aziz et al., 2017). In addition, the groundwater quality depends on the result of the hydrogeology of the location, the rock composition, weathering in the source area, and composition of the mineral sediments that are the basic factors controlling the chemical composition of the water. Also, the water from Bakhtiari formation and recent deposits has in general good quality, as well as the waters from shallow wells, located near cities and villages, which are mostly contaminated, due to free seepage of sewage water (Stevanovic and Iurkiewicz, 2009).

3. Results and discussions

Usually, the average daily consumption per person in the city can be found by dividing the amount of water used for all purposes in the particular area (such as daily consumption of people, washing, irrigation of gardens, industries, markets, departments, schools, places of worship ... etc.) by the number of population in that area. This indicates that everyone has the right to consume the quantity specified by the concerned departments. For example, Directorate of Water in Erbil City provides an amount of 380 liters/person/day (General Directorate of Water and Sewerage, Kurdistan Region-Iraq, 2020). Therefore, any use of more than the specified amount available for each person leads to a decrease in the quantity for another person (or other people). For example, a person builds a garden next to or opposite his house and irrigates the garden with potable water, and on the other hand, there are other houses that do not reach them with the water intended for them. Washing cars in front of houses and garages is the other example of wasting water. This is a transgression on the rights of others. It should be noted that due to excessive use of drinking water.

The current study verified that the Erbil City directly provided its required quantity of water, about 85 %, from the Greater-Zab River. This water is provided by the Directorate of Water in Erbil City throughout water treatment plants, which are responsible for the acquiring the required amount of water for each inhabitant. Some of the groundwater that is pumped out from the wells is subjected to pollution via nitrates and pathogens. This water source also has a higher nitrate and E.coli level than the water that comes from the Ifraz water treatment plants. However, when the pathogen (coliform, and E.coli) amounts increase, the potential for creating higher levels of disinfection by-products also exist which is also a water quality concern. Meanwhile, Erbil continually imports this treated water by Ifraz Water Treatment Plants which contains disinfection agent (Mustafa et al., 2021). Chlorine gas is used for disinfection process in the Ifraz water treatment plants. The chlorine can react with naturally occurring materials in the water to form unintended by-products which may lead to health risks according to (Jadoon, 2015). It should be mentioned that the local authorities with the Directorate of Water Resources and Irrigation in Erbil City should set a monitoring network that would be required to observe the groundwater fluctuations and to avoid drilling extra illegal wells in the region, and to control water resources management for Erbil City.

Additionally, it is recommended to use further surface water for water supply in Erbil City, instead of using groundwater. Providing treated wastewater for irrigation, washing, construction, and recharging groundwater is another sustainable solution and management for water in Erbil City. According to Shareef and Muhamad (2008) Water contamination is a serious problem, also population and industry are trying to make greater demands on the water resource, that demand the problem escalates. Based on Shekha's (2008) study, about 20 % of the world's population lacks in safe drinking water and a half of the world's population lacks adequate sanitation.

4. Conclusions

Based on the results it can be concluded that the Erbil City requires appropriate water management system because the sustainability of the water management can play a fundamental role to maintain the source for the future challenges and for the future generation, as it is clear. The rapid growth of the global population and their activities cause the decrease of amount of water and increase of its demand. The study highly recommended to consider the sustainability of the water supply system. If this issue is not taken into consideration, the draught will cause irreparable problems. It is suggested to use more surface water via construction further water treatment plant, instead of using groundwater wells. Reusing of treated wastewater for irrigation, washing, construction and recharging groundwater can be seen as a sustainable plan and management for the water sector in Erbil City.

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Održivost upravljanja snabdevanja vodom u Erbilu u kontekstu održivog razvoja

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Upravljanje snabdevanjem vodom

I Z V O D

Jedan od najvažnijih principa zastupljenih na dnevnom redu po pitanju održivog razvoja jeste raspodela vode i snabdevanje budućih generacija. Cilj rada je procena održivosti količine i kvaliteta izvora vode za Erbil, kao i njihova sigurnost i bezbednost na osnovu standardnih ograničenja. Prvi korak je bio izračunavanje količine i potražnje vode na osnovu prilagođene skale, a zatim su proučavani podaci dobijeni od direkcija za vode koji se odnose na površinske i podzemne vode za ispitivano područje. Ispitivanje je bilo usmereno na upravljanje vodosnabdevanjem i glavne faktore koji su uticali na nedostatak održivosti. Sledeći korak je bio razmatranje odgovarajućeg rešenja za te probleme, kao što je izbegavanje bušenja ilegalnih bunara podzemnih voda i bolje upravljanje vodoprivrednim sektorom. Upotreba dodatnih površinskih voda dobijenih nakon izgradnje dodatnih postrojenja za prečišćavanje vode se može smatrati alternativom za potrošnju podzemnih voda. Ponovno korišćenje prerađene kanalizacijske vode za potrošnju i dopunjavanje podzemnih voda se takođe može smatrati održivom strategijom za snabdevanje vodom u Erbilu.

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Wastewater sludge characteristics, treatment techniques and energy production

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A B S T R A C T

The research presents an overview on sludge types, characteristics, and methods of treatment. Additionally, using the sludge as an energy source for future plans was studied as well. The paper focused mainly on analyzing different sludge characteristics based on the previous studies. Wastewater sludge produced from the primary, secondary, and tertiary treatment processes was analyzed. It was mainly composed of many organic and inorganic materials. Some of the materials were removed by physical and other required chemical or biological processes. Most of the sludge was solid, semi-solid, and muddy with the harmful substances such as proteins, phenols, and hazardous materials. The study explained different methods of energy production as well. At the end, it was concluded that every type of sludge could provide energy and be a basic financial product for the selected area, and keep environment safely and healthy as well. The calculated quantity of dry sludge for 1,000,000 inhabitants in Erbil City, Kurdistan Region-Iraq, was 50,000 kg/d, which produced calorific value of $9.5 \cdot 10^7$ K. cal./day. Furthermore, the essential area for under drain sand bed area was 5,100 m^2.

1. Introduction

Nowadays, due to various human activities and rapid increasing of the population growth, the waste production is highly increased, especially for those cities which face these problems, and require proper managing of this disposed wastes, as well as, switching to alternative energy sources for developing Erbil economy infrastructure. Erbil City is the Capital of Kurdistan Region, Iraq. However, most undeveloped countries deal with the waste production without getting benefit from it. Meanwhile, the use of proper techniques will not cause such big problems, although, it will have an effect on the surrounding environment. For these reasons, this important topic has been selected in order to evaluate the produced sludge form Erbil City's wastewater, and to familiarize future researchers with this problem and motivate them to try and find appropriate methods for sludge management and to help with the lack of energy sources form the obtained sludge amount. It is obvious that sludge types depend on the sources of sludge production, for instance, the sewage sludge has characteristics different from sludge produced from municipal wastewater. It should be considered that the high amount of sludge disposal causes difficulty, therefore the optimization of the existing system and final decision is very crucial for the study area. Though, due to various sludge characteristics and large amount of water

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content, it can be used as a potential energy source for future if it is properly used (Kurniawan et al., 2018). It is also observed that anaerobic digestion is preferable, for variety of sludge wastewater, but this method is limited in general (Vatachi, 2019).

The current study reviewed numerous previous papers, in order to find a suitable solution for the selected waste problems in the study area. Unfortunately, this subject has not been studied up to now. Therefore, the problems were analyzed and the appropriate methods of treatment were determined for each case based on the previous experiences in this subject. Karagiannidis et al. (2011) worked on sewage sludge production and utilization in Greece. Furthermore, Johnson et al. (2014) published a paper on waste sludge in industry. Kollmann et al. (2017) worked on energy production from wastewater practical aspects of integrating a wastewater treatment plant. Moreover, Demirbas et al. (2017) published their works on the sludge. Guo et al. (2019) published a research on green energy produced from wastewater treatment plant (WWTP). De Azevedo et al. (2019) carried a research on sludge industry and safe disposal method for the environment. Salama et al. (2020) worked on activated sludge for sewage treatment plant in Morocco. On the other hand, all the studies suggested several methods of energy production from different sludge types and sources in different countries as well. Dempsey and Jeon (2001) studied sludge characteristics produced from mine drainage. Also, Janczukowicz et al. (2001) worked on activated sludge from a sequencing batch reactor. Degaard Paulsrud and Karlsson (2002) conducted a research on wastewater sludge. Later, Mesdaghinia et al. (2004) studied characteristics of sludge produced from wastewater treatment plant. Sievers et al. (2004) published a research on sludge treatment. Geng et al. (2007) carried out the investigation on sludge characteristics. Asia et al. (2006) published research on sludge characterization for petroleum industry. Aziz et al. (2012) reported that powdered activated carbon improved sludge characteristics, especially Sludge Volume Index (SVI). Next, Nei et al. (2014) determined the compost form sludge of the sewage of pharmaceuticals. Mills et al. (2014) studied evaluation of the future sewage sludge for energy technologies. Ayoub, et al. (2016) worked on energy production from wastewater sludge. Qian, et al. (2016) carried out the investigation on municipal sewage sludge treatment. Amudha et al. (2016) conducted a research on sludge efficiency. Additionally Kim et al. (2017) published a research on sewage sludge treatment.

The review article took those studies as a fundamental, especially those that discussed the most common technologies that can be used for the production of sludge from wastewater. The study also performed an assessment of the impact of obtained sludge on the environment. Furthermore, it was focused on other challenges to convert waste for energy sources like power, heat, and gas as well. In addition, the study evaluated economic and environmental safety aspects by considering sustainability of the environment (Oladejo et al., 2018).

Erbil City faces the deficit in power and energy production. It is clear that there is a gap between the available sources and demand, and for this reason, it is important to implement new sources of energy production and cost as well. In addition, the production of sludge in the selected city is highly increased, due to rapid growth of the population, urbanization, developing several projects, and industrial activity. The use of sludge from those sources should be managed in order to decrease the disposing impact on nature.

To date, a number of researches published articles on wastewater quality, treatment, and reusing in Erbil City, Kurdistan Region-Iraq (Aziz, 2004; Amin and Aziz, 2005; Bapeer 2010; Shekha et al., 2010; Aziz and Ali, 2018; Aziz, 2020; Aziz et al., 2020). But so far, there is no published work on sludge characteristics, treatment, products, and energy production in the Erbil City and in Kurdistan Region-Iraq. Consequently, the objective of this research was to study the sludge quality, treatment methods, and outcomes of the sludge processing. Additionally, the current work was focused on the sludge quantity and obtained energy from sludge processing in Erbil City.

2. Produced sludge in the WWTP

The study focused on the review of the previous studies, presentation of the way of disposing sludge and converting it to potential energy, and minimization of the sludge volume in the environment. Usually, sludge is produced from sewage or wastewater treatment processes (Figure 1). It is mainly classified into two types called sludge and activated sludge that can be provided in the activated sludge treatment processes.

Normally, WWTP includes primary, secondary, and advanced treatment processes. Sludge is produced throughout several wastewater treatment processes, Figure 1. Sludge comprises of liquid and solids. Most part of the sludge is liquid part. Sludge is categorized into the following groups:

- Primary sludge: contains settleable solids carried in the raw wastewater;
- Secondary sludge: consists of biological solids, as well as extra settleable solids.
- Sludge produced in advanced treatment process: may contain viruses, heavy metals, phosphorous, or nitrogen.

The objectives of the sludge treatment are:

- To decrease moisture content in the sludge (Volume reduction);

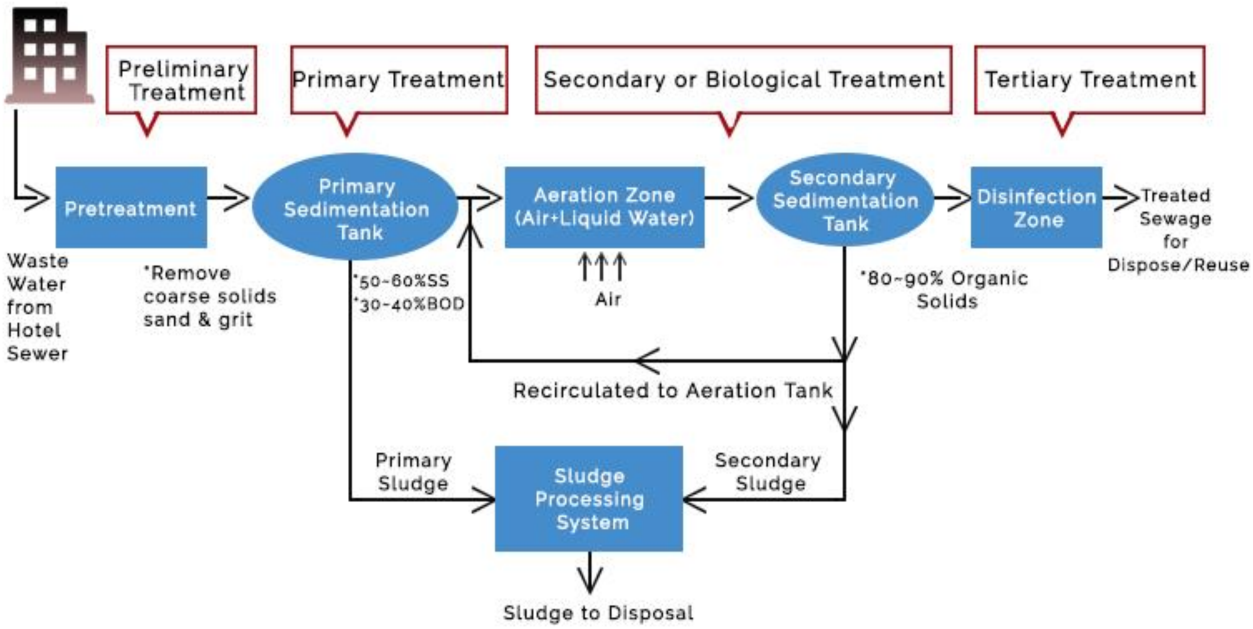

Figure 1. Produced sludge at typical WWTP (http://neoakruthi.com/blog/sewage-treatment-plant-for-hotels.html)

- To remove organic matters;
- To destroy microorganisms; and
- To eliminate toxic materials.

3. Sludge characteristics

Wastewater sludge type is solid, semi-solid, or muddy liquid where each of those consists of the various organic or non-organic materials, heavy metals, pesticides, polycyclicaromatic, phenols, and many other materials. The main characteristics of sludge are explained in (Metcalf and Eddy, 2014) as follows:

- Screening: It contains both organic and inorganic matter;
- Grit: It involves organic and inorganic matter, especially fats and grease;
- Scum/Grease: It consists of the floatable materials, oil and grease, animal fats, food wastes, vegetable and fruit skins, paper and cotton, cigarette tips, and plastic materials;
- Primary sludge: It is mostly gray and slimy;
- Sludge from chemical: It contains much iron;
- Trickling-filter sludge: It is produced from trickling filters flocculent, and relatively inoffensive when fresh;
- Aerobically digested bio solids: It has a flocculent appearance;
- An aerobically digested bio solids: Those contain large quantity of gas or hot tar, burnt rubber that produce methane gas; and
- Compost: Such as recycled compost, wood chips which can be used for composting.

Most of the conventional municipal wastewater sludge is mainly composed of sludge from primary sedimentation tanks (composed of organic and inorganic materials coming from the raw wastewater) and sludge from the secondary sedimentation tanks following biological treatment (influenced by the wastewater source and primary sedimentation tank operation). This sludge is also called activated sludge which involves the excess microorganism cells from the biological treatment process.

Each type of wastewater requires definite treatment process and generally it depends on the source and characteristics of the unprocessed wastewater. Accordingly, produced sludge from different treatment processes has various degrees of sludge quality. Table 1 illustrates typical characteristics of primary and secondary sludge. Details of sludge characteristics are shown in Table 2.

Yan et al. (2009) reported that numerous heavy metals were available in the wastewater sludge. Essentially, phosphor and potassium have both a high fertilizer value, while silica suggests good properties for soil stabilization applications (CORE, 2022).

These characteristics offer good chance for the recovery of fertilizers and construction materials from sewage sludge (CORE, 2022). It can be observed that wastewater sort and treatment technology have the effect on the sludge characteristics.

Table 1
Typical properties of primary and secondary sludge (Metcalf and Eddy, 2014)

Parameter	Primary sludge	Secondary activated sludge
pH	55 - 8.0	6.6 - 8.0
Alkalinity (mg/L as $CaCO_3$)	600 - 1,500	550 - 1,200
Total solids % (TS)	4 - 9	0.6 - 1.2
Volatile solids (% of TS)	65 - 80	60 - 85
Protein (% of TS)	18 - 30	30 - 40
Fats and grease (% of TS)		
Ether soluble	5 - 30	-
Cellulose (% of TS)	8 - 16	-
Nitrogen (N. % of TS)	1.4 - 4.2	2.5 - 5.0
Phosphorus (P_2O_5 % of TS)	0.6 - 2.9	3 - 10
Organic acids (mg/L as HAc)	250 - 1,800	1,000 -
Energy content, kJ/kg TS	24,000 - 28,000	18,000 - 23,000

Table 2
Summary of previous studies for sludge types and techniques

No.	References	Sludge sources	Techniques	Parameters
1	Janczukowicz et al. (2001)	Activated Sludge	Continuous flow	SVI: 20 - 600 ml/g
			Discontinuous flow	100 - 500 ml/g
			Continuous flow with mixing tank before the reactor	70
			Sequencing batch reactor (SBR)	40 - 60
			Experimental SBR	30 - 50
2	Uygur and Kargi (2004)	Landfill leachate	SBR	pH 8.6 COD mg /L NH_4N mg /L $NO_3.N$ mg /L $PO_4.P$ mg /L TSS mg /L TS mg /L Salinity % Dissolved oxygen mg /L
3	Kupka et al. (2008)	Municipal		13.8 (LCV)
4	Fonts et al. (2009)	Municipal		12.3 (HHV)
5	Aziz et al. (2012)	Landfill leachate	Powdered activated carbon (PAC)	SVI<100 mL/g
6	Manara and Zabaniotou (2012)	Primary treatment		4,200 (kWh/t)
		Biological treatment		4,100 (kWh/t)
		(Low) Biological treatment		4,800 (kWh/t)
		(Low and Mid)		
		Primary and Biological		4,600 (kWh/t)
		(Mix) Digested		3,000

Table 2 Continued
Summary of previous studies for sludge types and techniques

No.	References	Sludge sources	Techniques	Parameters
7	Folgueras et al. (2013)	Municipal		17.75
8	Li et al. (2014)	Municipal		15.59 (HHV)
9	Magdziarz and Werle (2014)	Thermal power plant		13.12 (HHV)
10	Chiou and Wu (2014)	Pulp industries Textile Industries		8.73 5.1
11	Atienza-Martinez et al. (2015)	Digested (municipal)		12.79 (HHV)
12	Ayoub et al. (2016)	Sewage	Chemical Precipitation	Biogas 440 m^3/d Methane 286 m^3/d Electric power 400 KWh/d
13	Vatachi (2019)	Wastewater	Anaerobic digestion Combustion Pirolysis Gasification	Biogas Flue gas Bio char Bio oil Synthesis gas Tar Heat - Ash

4. Methods of sludge treatment

Generally, there are various treatment processes available to deal with the sludge, which are mainly based on the sludge composition types. For instance, for sewage sludge the methods of lime stabilization, dewatering, thickening, drying, composting, and the aerobic methods are applicable. Although, sludge that consists of nutrients can be used for fertilizer purposes. However, there is not any treatment process required for purifying the sludge that is produced from sewage. Meanwhile, toxic materials produced as a result of industrial and commercial treatment processes that are thrown into the sewage system can be used for farmlands. Moreover, some of the sludge types require to be disposed on landfilleds or incinerated depending on its composition.

However, the available sludge from WWTP has the vital role in environmental engineering, because it requires a treatment before disposing (Demirbas et al., 2017).

Sludge should be treated for the following purposes: reduction of moisture content (Volume reduction), removal of organic matter, destruction of microorganisms, and removal of toxic material.

The important techniques that should be taken into account are thickening, digestion, conditioning, dewatering, heat drying, and incineration. After the following techniques the final treated sludge can be disposed into the environment.

4.1. Thickening

Thickening reduces moisture content of sludge. Types of thickening process are: gravity thickening, air flotation, and centrifugation.

4.2. Digestion

There is aerobic and anaerobic decomposition of sludge. Later, the digested sludge can be sent to mechanical filters or sand beds (Vatachi, 2019), Figure 2. Table 3 illustrates typical chemical composition and properties of untreated/digested sludge.

4.3. Conditioning

Conditioning enhances the drainability of digested sludge. Methods adopted are elutriation (involves passage of air to separate particles), chemical conditioning (addition of coagulants), freezing etc.

4.4. Dewatering

The aim of dewatering is to reduce volume of sludge and increase concentration of bio solids, Figure 9. Dewatering can be achieved on sand drying beds or bed filters, Figure 3 (EEA, 1998).

4.5. Heat drying

Heat drying process is carried out in kiln at 350 °C. It decreases water content. Dried sludge is used as soil conditioner.

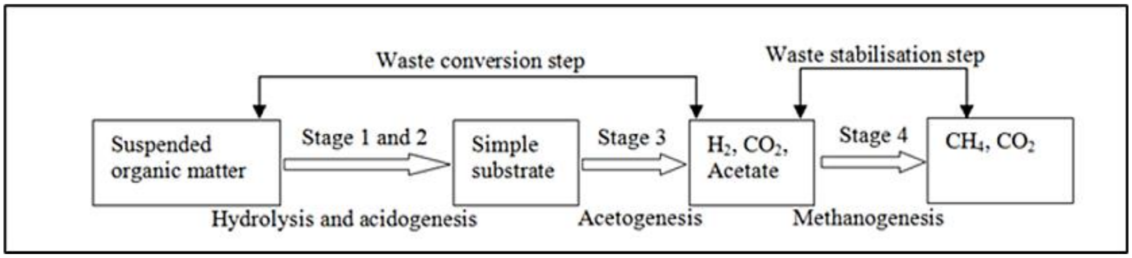

Figure 2. Stages of anaerobic digestion (Vatachi, 2019)

Table 3
Typical chemical composition and properties of untreated/digested sludge (Yan et al., 2009)

Item/Sludge	Untreated Primary	Digested Primary
Total dry solids (TS), %	2.0 - 8.0	6.0 - 12.0
Volatile solids (% of TS)	60 - 80	30 - 60
Grease and fats (% of TS)		
Ether soluble	6 - 30	5 - 20
Ether extract	7 - 35	-
Protein (% of TS)	20 - 30	15 - 20
Nitrogen (N,% of TS)	13 - 4	16 - 6.0
Phosphorous (P_2O_5, % of TS)	0.8 - 2.8	1.5 - 4.0
Potash (K_2O, % of TS)	0 - 1	0 - 30
Cellulose (% of 'TS)	8.0 - 15.0	8.0 - 15.0
Iron (not as sulfide)	2.0 - 4.0	3.0 - 8.0
Silica (SiO_2, % of TS)	15.0 - 20.0	10.0 - 20.0
Alkalinity (mg/L as $CaCO_3$)	500 - 1,500	2,500 - 3,500
Organic acids (mg/L as HAc)	200 - 2,000	100 - 600
Energy content	10,000 - 12,500	4,000 - 6,000
pH	5.0 - 8.0	6.5 - 7.5
Polymer		
Protein (sludge)	217 - 353	
Proton (EPS)	28 - 56	
Humic substances (Sludge)	73 - 195	
Humic substances (EPS)	17 - 51	
Carbohydrate (Sludge)	55 - 93	
Carbohydrate (EPS)	5.7 - 40	
Total extracted (EPS)	52 - I 19	

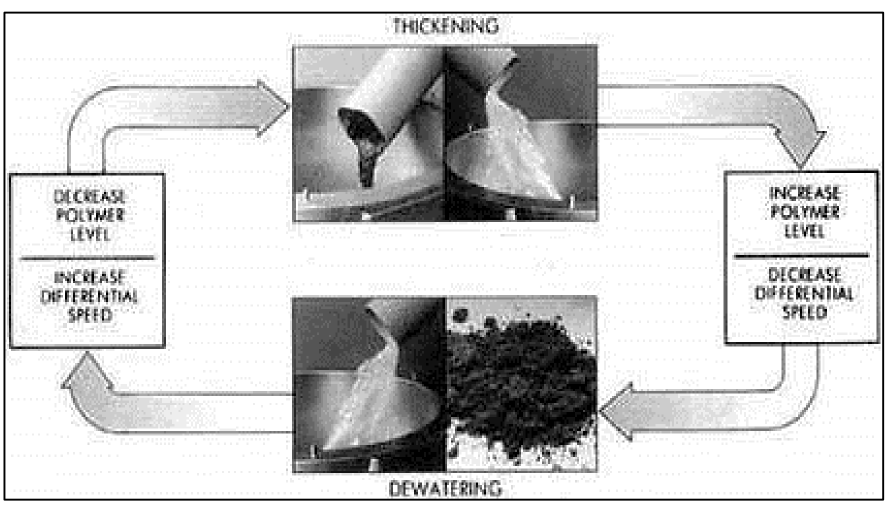

Figure 3. Sludge dewatering (EEA, 1998)

4.6. Incineration

Incineration is performed at temperature from 650 °C to 750 °C to burn the organic matter and other materials, Figure 4. It represents the combustion of sludge. Residual ash after incineration process is send to solid waste landfill site.

Each sludge treatment method has its benefits and shortcomings. Selection of a suitable sludge treatment system depends on land availability, energy, cost of construction and operation/maintenance, objective of the treatment etc.

Details of sludge treatment processes are shown in Table 4. Finally, Kumar et al. (2017) presented the most appropriate methods for sludge treatment in Figure 5.

Additionally, Figure 6 illustrates details of the typical sludge quantities in wastewater treatment plant.

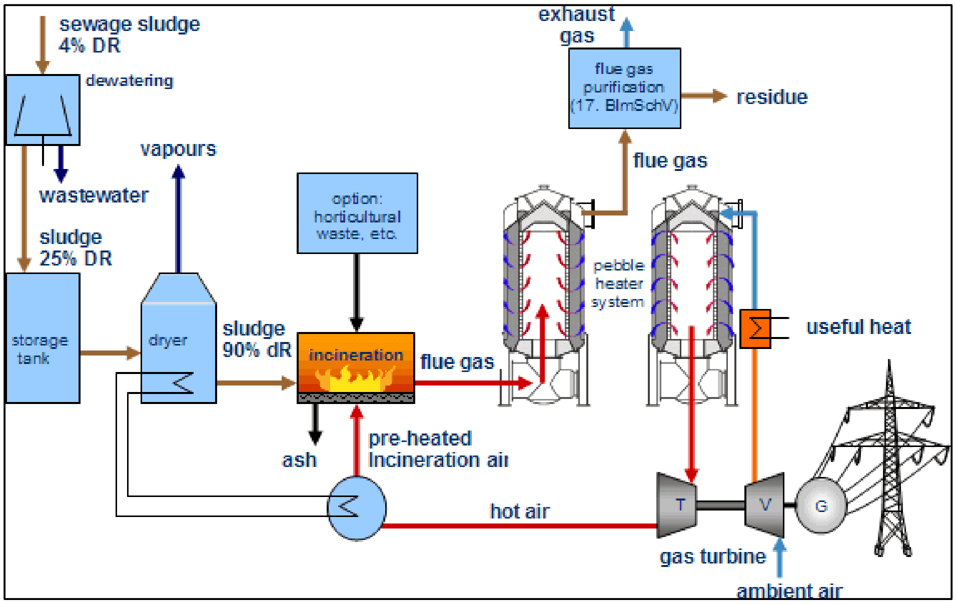

Figure 4. Incineration process

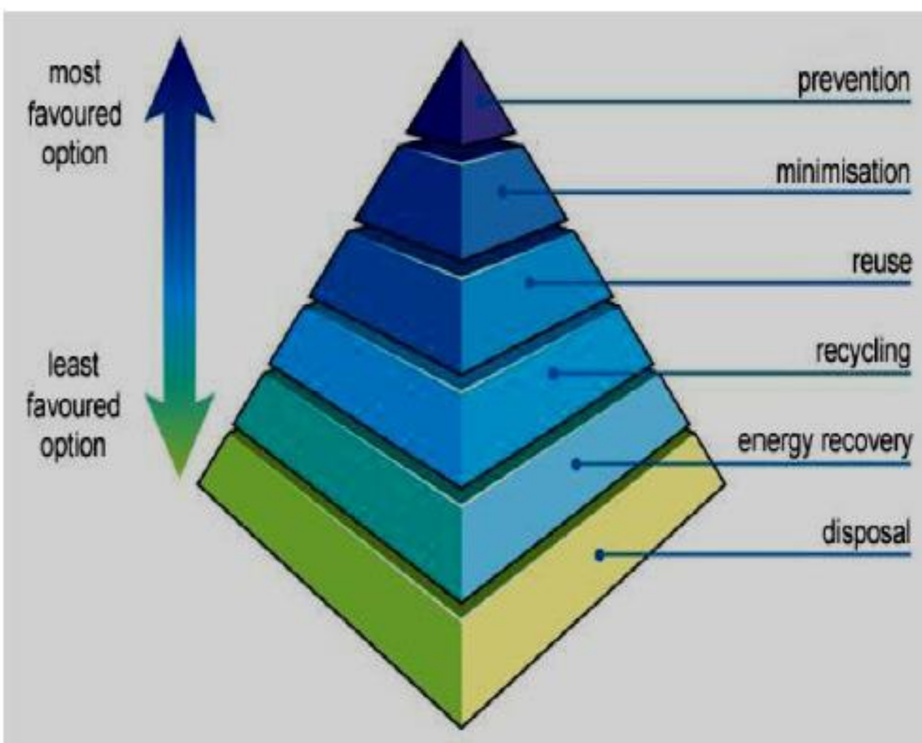

Figure 5. Most appropriate methods for sludge treatment (Kumar et al., 2017)

Table 4
Details of sludge treatment processes (COW, 2021)

Sludge treatment stage	Principal purpose of sludge treatment stage	Sludge treatment process	Specific purpose of treatment process	Classification by type of treatment
Thickening	To thicken sludge to reduce volumetric capacity of subsequent treatment and improve performance of stabilisation processes	Gravity thickening		Physical
		Elutriation	Improves gravity thickening	Physical
		Flotation		Physical
		Centrifuging		Physical
Stabilisation	To reduce organic solids content of sludge and thus reduce unpleasant odours when sludge disposed of or recycled; to reduce pathogens; to render sludge more readily dewatered	Anaerobic digestion (unheated)		Biological
		Anaerobic digestion (heated)		Biological
		Secondary digestion (unheated)		Biological
		Aerobic digestion		Biological
		Chemical stabilisation		Chemical
		Pasteurisation	Destroy pathogens	Physical
		Composting	Agricultural reuse	Biological/ Physical
Dewatering	To reduce volume of sludge to be disposed of; to render sludge easier to transport and mechanically handle; to reduce fuel used in drying or incineration processes	Drying beds	Sludge solids more than 45 %	Physical
		Belt presses	Sludge solids - 1 to 25 %	Chemical/ Physical
		Centrifuges	Sludge solids - 1 to 25 %	Chemical /Physical
		Plate presses	Sludge solids - 2 to 40 %	Chemical/ Physical
		Vacuum filters	Sludge solids - 1 to 20 %	Chemical/ Physical
Drying/Incineration	To considerably reduce volume prior to disposal	Thermal drying	Sludge solids lower than 20 %	Physical
		Incineration	Produces inorganic ash	Physical
Disposal	Safe disposal if reuse not possible	Sanitary landfill		Physical
Reuse/ Recycling	Alternatives to disposal of sludge by obtaining some beneficial use from sludge	Agriculture	Improves soil and productivity	
		Vitrification	Inert end product	Physical

Table 4 Continued
Details of sludge treatment processes (COW, 2021)

Sludge treatment stage	Principal purpose of sludge treatment stage	Sludge treatment process	Specific purpose of treatment process	Classification by type of treatment
		Oil from sludge	Product with fuel value	Physical
		Gasification	Product with fuel value	Physical

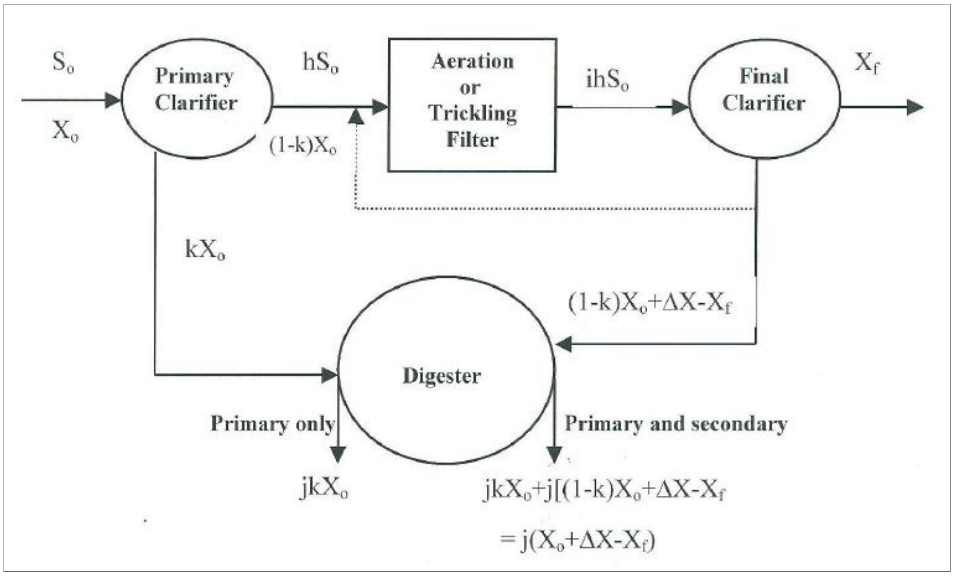

Figure 6. Details of the typical sludge quantities in wastewater treatment plant (http://www.eea.europa.eu/publications/GH-10-97-106-EN-C)

In order to determine the typical wastewater sludge in water treatment plant, the following description and terms should be known:

- S_o is influent BOD (mg/L);
- X_o is influent suspended solids (Kg/hr);
- h is fraction of BOD not removed in the primary clarifier;
- i is fraction of BOD not removed in the aeration tank;
- X_f plant effluent suspended solids (Kg/hr);
- k is fraction of X_o removed in the primary clarifier;
- j is fraction of solids not destroyed in digester;
- ΔX represents net solids produced by biological action (Kg/hr);
- Y is Yield = $\Delta X / \Delta S$; and
- $\Delta S = h\, S_o - ih\, S_o$.

Common sludge treatment processes are shown in Table 5.

Table 5
Common sludge treatment processes (EEA, 1998)

No.	Treatment process	Reason for importance
1	Sludge degritting	to apply centrifugal forces in a fluid system.
2	Dewatering	for reducing the moisture content of the sludge.
3	Drying	to make the water content suitable for processing the sludge or fertilizer.
4	Drying lagoons	The sludge drying lagoons, which are suitable only for digested sludge treatment,
5	Filtration	Vacuum filtration is used for dewatering water from raw and digested wastewater sludge.
6	Stabilization	Sludge is stabilized to reduce its pathogenic content, to remove irritating odors from the surface, and to reduce or eliminate the potential for imperfections.
7	Blending	to form a uniform blend.
8	Thickening	For increasing the solids content of the sludge.
9	Conditioning	to improve its dewatering characteristics.
10	Chemical precipitation	to remove metal ions.

Table 5 Continued
Common sludge treatment processes (EEA, 1998)

No.	Treatment process	Reason for importance
11	Heat treatment	For heating in a pressure vessel.
12	Composting	it is to stabilize biodegradable organic matter, to destroy pathogenic organisms, and also to reduce the volume/amount of waste.
13	Anaerobic digestion	The process involves the anaerobic reduction of the organic material with biological activity in the sludge.
14	Sludge digestion	In this stage the organic solids are decomposed into three types of sludge: primary sludge, secondary sludge, and digested settled sludge.
15	Aerobic digestion	the anaerobic reduction of the organic substance with biological activity in the sludge.
16	Reuse as fertilizer	It is used to make fertilizer.
17	Activated sludge	the activated sludge process is oxidation of organic substances
18	Sulfur removal	When sludge contains high amounts of sulfur compounds, problems may occur in operating such anaerobic digestion process. Sulfide may inhibit the methane formation, and it also forms hydrogen sulfide gas which is toxic and corrosive.
19	Cement production	It can be used as a for cement in production.

5. Sludge products

The produced sludge can be used as composting material, construction material (bricks and cement and road pavement), fuel and biogas, soil amendment, and in agriculture (Kumar et al., 2017). Figure 7 and 8 illustrate sludge products. Pöykiö et al. (2019) published research on using sludge as soil improver and fertilizer product.

A list of sludge handling and treatment steps and disposal/reuse paths is set out in Figure 8. All wash waters and liquors formed in the course of cleaning (e.g. sand filter backwashing) and dewatering (e.g. dewatering of sludge) must be returned to the works inlet; in no circumstances may they be discharged into a nearby watercourse owing to the fact that they contain high concentrates of polluting materials (COW, 2021).

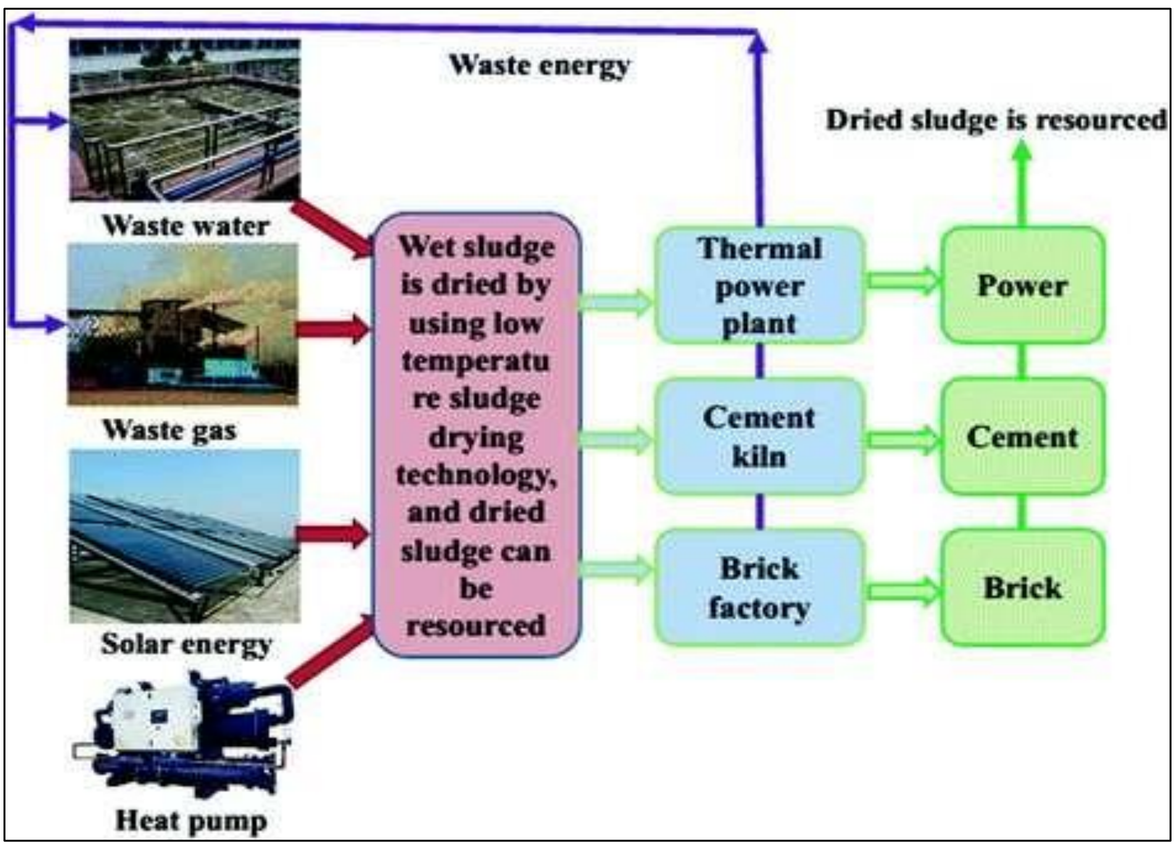

Figure 7. Sludge products

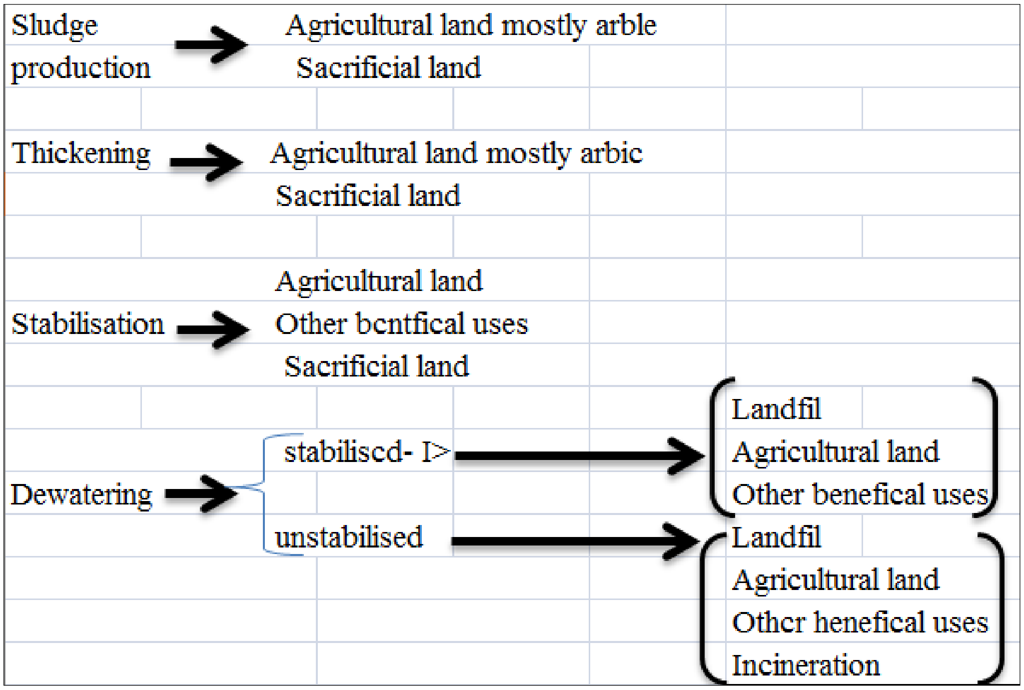

Figure 8. Principal sludge treatment and disposal routes (EEA, 1998)

6. Sludge to energy

Sludge to energy processes are shown in Figures 9 to 10. Furthermore, biogas production in several countries is illustrated in Table 6. Biogas production in several countries is documented in Table 7.

Usually, one of the most common waste management issues is wastewater sludge, which directly impacts the sources that can cause damage global environment. For this reason, it is required to minimize those wastes, and it can be used as an-alternative source of power and energy generation in the area. Nowadays, most of the countries focus on the energy production.

Using anaerobic digestion to provide energy from both types of wastewater sludge can obtain low-cost fuels compared with natural gas (Vatachi, 2019). On the other hand, Kurniawan et al. (2018) conducted a research on the wastewater sludge and then converted it to energy.

Oladejo et al. (2018) studied sludge converting to energy. Quansah et al. (2018) published a study on sludge wastewater management via conventional wastewater treatment process. Vatachi (2019) presented a study on converting sludge of the wastewater to energy.

Đurđević et al. (2020) investigated sewage sludge treatment by using the thermal and Analytical Hierarchy.

The study of Bora et al. (2020) presented producing energy from sludge.

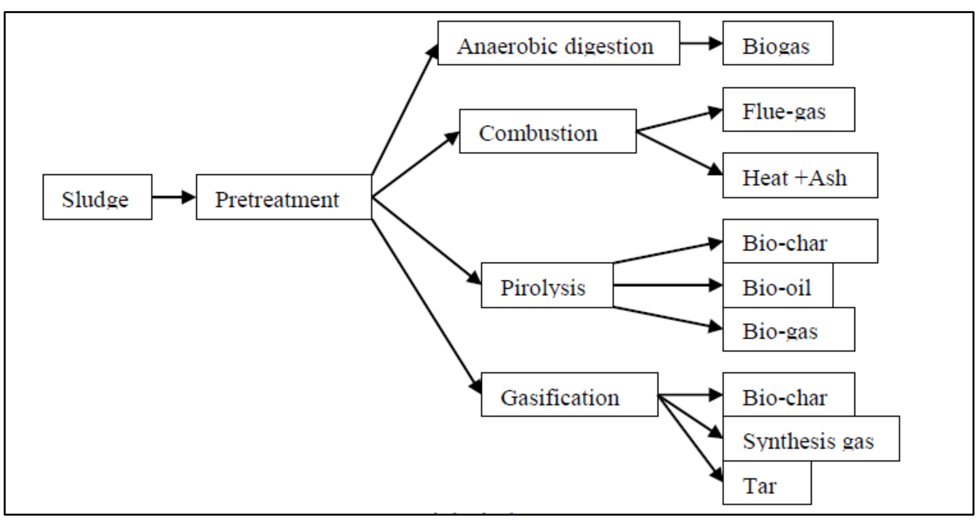

Figure 9. Potential Sludge-to-Energy Recovery Routes (Vatachi, 2019)

Table 6
Fuel types, emission and residue (Kurniawan et al., 2018)

No.	Technology	Feedstock	Feel Types	Energy Content Calorific Value	Emissions/ Residues
1	Pyrolysis	Mixed Sludge	Gas, liquid	High GCV 29.9 MJ Nm-3	NO, CO_2, CO
		Oil Sludge		35.8 MI Nni-3	Combustible gases
2	Fast Pyrolysis	rice waste and sewage sludge	Gas, Bio-oil	N/A	Char/solid
3	Fast Pyrolysis	sewage sludge	Liquid	HHV/NET Bio-oil 23.9 - 279 MJ/kg	Ash (57.9 - 75.1 wt)
4	Pyrolysis	Domestic, Commercial, Industry sludge	Gas, Liquid	(GCV at 550 °C) commercial: 825 kJ/kg: domestic. 660 kJ/kg industrial: 370 kJ/kg	syngas (CO, CO_2, CH_4, C_2H_4, and H_2)
5	Pyrolysis	Wet wastewater sludge	Syngas	HHV = 24,000 J/kg	C_2H_4, C_2H_6, C_3H_6, C_3H_8
	Gasification		Gas	HHV17500 19,500 J/kg	
6	Pyrolysis	Wastewater Biosolids	Py-gas Py-oil	2.1 MJ/ kg - 3 MJ/ kg feed biosolids	CH_4, CO_2
7	Fast Pyrolysis	Domestic WWTP	Liquid	N/A	Ash, HCs, N_2, CO_2
8	Co- gasification	Woody biomass and sewage sludge	Py-gas, Py-oil	4.5 MJ/Nm^3 (LHV average)	non condensable gas, char
9	Co- pelletization	Municipal	Py-gas Py-oil	8.43 kj/L	non condensable gas, char
10	Pyrolysis - Torrefaction	Digested (municipal)	Py-gas, Py-oil	HHV Char 25 - 30 MJ/kg JJV Liquid 41 - 43 MJ/kg	CO_2. non condensable gas, char
11	Pyrolysis	Municipal	Py-gas. Py-oil	1,934 ± 580 to 2,721 ± 321 K cal./m^3(NTP)	Non-condensable gas

Table 7
Biogas production in several countries (Hanum et al., 2019)

County	Year	Total biogas production (From agricultural residues, industry wastewater, bio-waste, landfills and sewage sludge		Biogas production in WWTPs (Only form sewage sludge)	
		Number or plants	[GWh/y]	Number or plants	[GWh/y]
Australia	2017	242	1,587	52	361
Austria	2017	291	3,489	39	18
Argentine	2016	62	n.a	n.a	n.a
Belgium	2015	184	956	n.a.	n.a
Brazil	2016	165	5219	10	210
China	2014	11,500	90	2630	n.a
Czech Republic	2015	554	2,611	n.a.	n.a
Denmark	2015	156	1,763	62	281
Filand	2015	88	623	16	152
France	2017	687	3527	88	442
Germany	2016	10,431	55,108	1258	3,517
India	2015	83,540	22,140	n.a.	n.a
Ireland	2015	28	202	n.a	n.a
Italy	2015	1,491	8212	n.a.	n.a
Japan	2015	n.a.	30,200	2,200	n.a
Norway	2017	39	738	24	223
Korea	2016	110	2,798	49	1,234
Pakistan	2015	4,000	n.a	n.a.	n.a
Poland	2015	277	906	n.a.	n.a
Switzerland	2017	634	1,409	475	620
Spain	2015	39	962	n.a.	n.a
Sweden	2017	279	1,200	139	n.a
Sri LanKa	2013	6,000	n.a	n.a	n.a
Thailand	2014	n.a.	1,500	n.a.	n.a
Netherlands	2015	268	3,011	80	541
United Kingdom	2016	967	26,457	162	950
United States	2017	2,100	1,030	1,240	n.a
Malaysia	2017	n.a.	482	35	247

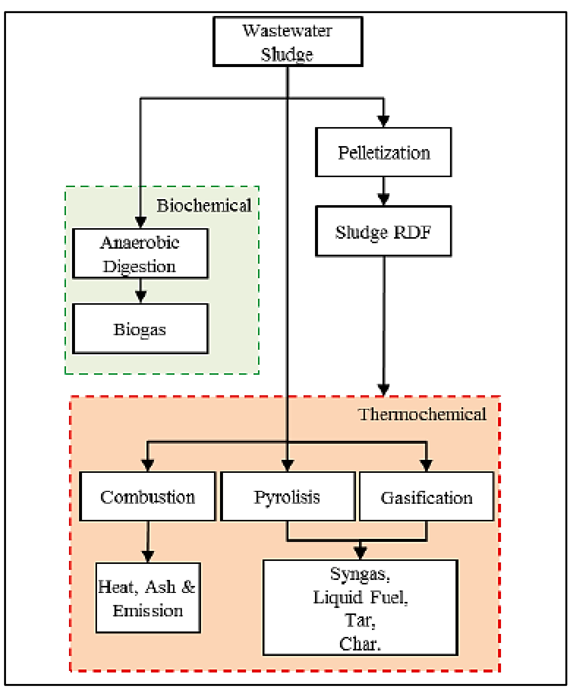

Figure 10. Routes for sludge energy recovery (Kurniawan et al., 2018)

According to Mills et al. (2014), the United Kingdom water industry generates about 800 GWhpa of electrical energy from the sewage sludge. Traditionally energy recovery from sewage sludge features anaerobic digestion with biogas utilization in combined both heat and power systems. However, based on Geng et al. (2007), sludge and primary sludge, including 20 % of the secondary sludge from a paper mill, were characterized as suitability for the producing of medium density fiberboard. On the other hand, Ayoub et al. (2016) presented in their study that the sewage treatment plant can be used with reducing the capital costs by 26 % and running costs by about 20 %. The electricity can be produced from anaerobic digestion of sewage sludge as well.

Quansah et al. (2018) suggested that the on-site sanitation and centralized facility fecal sludge treatment techniques and management practices were deemed as the core basis of study. Furthermore, the study described anaerobic and aerobic phosphorous removal process (A/O) that wasselected as an efficient and cost-effective centralized facility sludge treatment technique.

7. Estimation of sludge amount

7.1. Sludge mass calculation

If a coagulation of a treatment plant with a flow rate of ($0.5 m^3/sec$) has the dosage of alum (23.0 mg/L), without adding other chemical materials, and the concentration of the raw water suspended solids is 37.0 mg/L, and the suspended solids concentration of the effluent is 12 mg/L, the amount of the sludge mass for each day can be determined in the following way:

- Given data:

Flow rate $Q= 0.5 m^3/s$
Concentration of Alum $C_{in1}=23.0$ mg/L
Concentration of Suspended Solids $C_{in2}=37.0$ mg/L
Concentration of Alum $C_{out}=12.0$ mg/L

- Obtaining the mass of sludge using Applying Mass Balance for steady state case, Figure 11:

$$\text{Mass in - Mass out = Accumulation [for Steady state case in = out]}$$
$$\text{Mass in = Mass out}$$
$$Q \cdot Cin1=23.0 \text{ mg/L} + Q \cdot Cin2 = 37.0 \text{ mg/L}= Q \cdot C\ out = 12.0 \text{ mg/L} + \text{Mass Sludge}$$
$$\text{Mass of sludge} = Q \cdot (Cin1 + Cin2 - C\ out)$$
$$\text{Mass of sludge} = 0.5\ m^3/s \cdot (23.0 \text{ mg/L} + 37.0 \text{ mg/L} - 12.0 \text{ mg/L})$$
$$\text{Mass of sludge} = 24\ m^3/s.\ \text{mg/L}\ (1{,}000\ L/m^3) \cdot (86{,}400 \text{ sec/day})$$
$$\text{Mass of sludge} = 2{,}073{,}600{,}000 \text{ mg/day (g/1,000 mg)} \cdot \text{(kg/1,000 g)}$$
$$\text{Mass of sludge} = 2{,}073.6 \text{ kg/day}$$

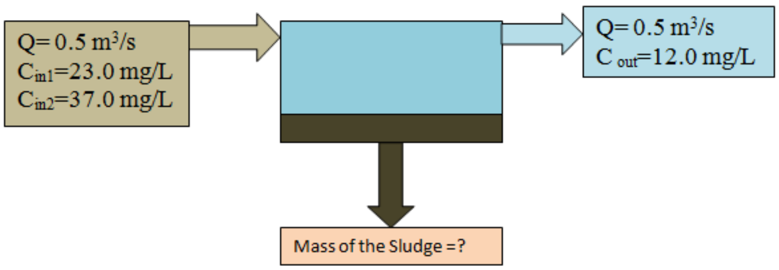

Figure 11. Details of produced sludge mass

7.2. Estimation of influent Sludge

The example is taken from Andreoli et al. (2007), for the conventional WWTP with anaerobic digestion of the mixed sludge, the number of the population is 67,000 inhabitants, and the size of the centrifuges for the dewatering of the sludge, the amount of the influent to the dewatering unit effluent form secondary digester is $46.9 m^3/day$. To determine the maximum influent sludge flow per hour:

$Q_{avg}= 46.9\ m^3/day = 1.95\ m^3/hr$
$Qmax= 1.5 \text{ (peak factor)} \cdot 1.95\ m^3/hr= 2.93\ m^3/hr$

To select the equipment such as centrifuge, the maximum sludge flow that will be dewatered and $6 m^3/hr$ is selected (one as operating and the another one as a spare unit).

The following operating hour can be selected based on the equation below:

$$\text{Operating time} \left(\frac{hr}{day}\right) = \frac{\text{Average influent sludge flow} \left(\frac{m^3}{day}\right)}{\text{Number of units} \cdot \text{Unitary capacity} \left(\frac{m^3}{hr}\right)} = \frac{46.9\ m^3/day}{1 \cdot 6\ m^3/day} = 8\ hr/day$$

8. Produced fuel

The subject is vital, especially for those areas that have a lack of waste management due to the financial and economic issues. Therefore, this research aimed to present the main existing problems and at the same time the methods of sludge treatment. The research can be used as an investigation reference for future challenges of energy production and also as a source of a big infrastructure and income for the current city and for the similar areas. Due to various sludge characteristics, it has proved that the presence of organic matter in sludge composition can be the basic source for future energy challenges. This energy requires the proper managing and conserving.

Normally, the wastewater sludge contains high quantities of the organic materials, and based on this, the value of the dry sludge can range within (10,000- 20,000 kJ/kg) based on (Vatachi, 2019), and the fuel value of house coal, crude oil and LPG is given below:

House coal: 27,000 - 31,000 kJ/kg
Heating oil: 42,500 kJ/kg
Butane and propane (LPG): 46,300 kJ/kg.

9. Calculation of sludge amount and Energy in Erbil City

Currently there is no central WWTP in Erbil City. Small size WWTPs are available in some investment residential projects and other locations such as Awamedica Pharmaceutical Company, Italy 2 Project, Green Land Project, Cihan City, and Rami Towers etc. Aziz (2020) reported that quantity of municipal WW at Tooraq Area is 5.56 m^3/s (480,384 m^3/d).

Population of Erbil City center is around 1,000,000 people.

Dry content of sludge per head per day = 0.05 kg/day (Singh and Singh, 2003).

Weight of dry content = 1,000, 000 · 0.05 kg/day = 50,000 kg/day

Total weight of wet sludge = 50,000 · (100/5) · 1.02 = 1,020,000 kg/day (Singh and Singh (2003) stated that for 5 kg dry weight, there is 100 kg of wet sludge with specific gravity of 1.02).

Volume of wet sludge = 1,020,000 kg/day/1,000 kg/m^3 = 1,020 m^3/day (Based on Singh and Singh (2003), density of wet sludge is 1,000 kg/m^3).

Required tank capacity = (1,020 · 100)/3 = 34,000 m^3/day (If only 3 % of fresh sludge is added to digester)

If 30 % added as margin for variations = 34,000 · (30/100) = 10,200 m^3/day

Total tank capacity = 34,000 m^3 + 10,200 m^3 = 44,200 m^3/day

Per capita volume = 44,200/1,000,000 = 0.0442 m^3/capita/day

The amount of produced gas = 1,000,000 · 0.02 m^3 = 20,000 m^3/day (volume of produced gas per capita per day is 0.02 m^3 (Singh and Singh, 2003)).

Calorific value for produced gas = 5,000 · 20,000 = 10 · 10^7 K.cal./day (If calorific value per m^3 is 5,000 K. cal.)

Calorific value become 9.5 · 10^7 K.cal./day (Based on Singh and Singh (2003), 5 % will be lost by radiation).

About 45,000 K.cal is required for one break H.P. per day with thermal efficiency of 35 %. Therefore, the gross power available from gas = 9.5 · 10^7 K.cal. /day/45,000 K.cal = 2,111.11 B.H. P.

Net power available from gas = 1,477.78 B.H. P./day (for 70 % mechanical efficiency)

The volume of the wet sludge is 1,020 m^3/day

If it is spread in a 20 cm thick layer on under drained sand beds,

The required area = 1,020 m^3/0.20 m = 5,100 m^2.

10. Conclusions

Normally, wastewater sludge contains moisture, heavy metals, organic and inorganic materials that can be used as the sources of energy. A number of techniques were offered for the wastewater sludge treatment; each method has advantages and disadvantages. Characteristics and quantity of produced sludge were presented. Several final products can be achieved from processing the sludge. The calculated amount of dry sludge in Erbil City was 50,000 kg/d which resulted in produced calorific value of 9.5 · 10^7 K. cal./day. Additionally, the required area for under drain sand bed area was 5,100 m^2.

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Karakteristike taloga iz otpadnih voda, tehnike obrade i proizvodnja energije

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Otpadne vode

I Z V O D

Ovo istraživanje predstavlja pregled vrsta taloga, njegove odlike, kao i metode obrade koje se koriste. Pored toga, proučavan je i talog kao potencijalni izvor energije. Rad se uglavnom fokusira na analizu različitih odlika taloga na osnovu prethodnih istraživanja. Analiziran je talog iz otpadnih voda nastao prilikom primarne, sekundarne i tercijarne obrade. On se uglavnom sastojao od mnogih organskih i neorganskih materijala. Neki od materijala su uklonjeni putem fizičkog postupka, dok su drugi zahtevali hemijski i biološki postupak. Talog je bio u čvrstom ili polu čvrstom stanju, kao i u obliku mulja koji je sadržao štetne supstance u vidu proteina, fenola i opasnih materijala. U radu su takođe prikazane različite metode proizvodnje energije. Na kraju se došlo do zaključka da bi svaka vrsta taloga mogla proizvesti energiju i biti osnovni finansijski proizvod za odabrano područje, a u isto vreme očuvati životnu sredinu. Izračunata je količina isušenog taloga za 1.000.000 stanovnika u Erbilu, Kurdistan, Irak, i iznosila je 50.000 kg/d, a dobijena toplotna vrednost je iznosila $9{,}5 \cdot 10^7$ Kcal/d. Pored toga, osnovna površina korita ispod isušenog taloga iznosila je 5.100 m^2.

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Future of water recycling – A review of the direct potable water reuse

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ABSTRACT

Population growth, increasing water stress, and water scarcity have influenced the consideration of the reuse of treated wastewater as a possible alternative water source. Currently, recycled water is mainly used in industry, agriculture, and landscape irrigation, and now, in certain parts of the world, recycled water is also used as drinking water due to the limited freshwater resources. To meet the future water supply needs, the direct potable water reuse could be studied as an alternative source of drinking water. Direct potable reuse can enhance sustainability and water supply reliability. This paper analyzes direct potable water reuse as a circular principle in water sector and compares several successful cases of direct potable water reuse in Namibia, South Africa, Texas and New Mexico. Countries that use direct potable reuse are successful examples of using wastewater to form sustainable and reliable water supplies, which is of great significance for the future.

1. Introduction

From 1950 to 2020, the population living in cities increased from 0.8 billion to 4.4 billion, and it is projected that by 2050 it will reach 6.7 billion (UN, 2018). Water demand exceeds the capacity of local water resources (Fajnorova et al., 2021) - two billion people live in countries under conditions of high water stress (UN-Water, 2018), four billion people experience severe water stress at least one month per year, and 1.8 billion people at least six months per year (Mekonnen and Hoekstra, 2016). Between 2008 and 2018, only Europe, Northern America, Central Asia, and Southern Asia reduced their water stress, and in all other regions, water stress worsened (UN-Water, 2021). On a global scale, water use is constantly growing, twice more than the population increase (Mainali, 2019). With continued population growth, rising living standards, and climate change impacts, it is estimated that the global water demand will grow by around 1 % per year until 2050 and that over half of the global population will live in water-stressed regions (UN-Water, 2019). This indicates that the population is at a threat of having a shortage of clean drinking water (Mancosu et al., 2015). Water scarcity (water demand exceeds water availability (He et al., 2021)) is a matter of human, economic, and environmental insecurity (Tortajada, 2020), and it is the crucial determinant of water security (He et al., 2021). In other term, water scarcity is the number one global societal risk (Zisopoulou and Panagoulia, 2021). Also, global water scarcity is a complex and dynamic problem (Dolan et al., 2021), and solving that problem is a challenge for continued human development and sustainable development goals achievement. Population growth and urbanization increase the number of water users and water consumption and influence water pollution and water scarcity (Ghernaout and Elboughdiri, 2019). Changes in rainfall patterns threaten to worsen these effects in many areas (Tortajada, 2020). Potential solutions to water scarcity involve two aspects: increasing water availability, and reducing water demand (UN-Water, 2018). Water demands can be met through:

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the development of local groundwater and surface water reservoirs, rivers, and lakes; development and implementation of inter-basin water transfer systems; desalination of brackish water and seawater; conservation; and potable reuse (WateReuse, 2020).

Currently, almost all parts of the world use the linear process of water use (Bertham and Sanahuja, 2019) - extraction, treatment, distribution, consumption, collection, treatment, and disposal/discharge into the environment. The natural environment acts as the buffer between treated wastewater and extracted drinkable water. With water scarcity and water stress all around the world, this is not an appropriate solution. Instead of a single-use process: take, treat, use, and discharge, wastewater can be reused as a valuable resource. The main goal needs to be closing the loop on water use. Recently, wastewater is recognized as a potential 'new' source of clean water for potable use (Tortajada, 2020), and this way of obtaining drinking water represents a circular water process. The process of using treated wastewater for drinking water is called potable water reuse (EPA, 2021). There are two types of potable water reuse: indirect potable reuse (IPR) and direct potable reuse (DPR). IPR uses an environmental buffer (a lake, river, or a groundwater aquifer) before the water is treated at a drinking water treatment plant (EPA, 2012). DPR involves the treatment and distribution of water without an environmental buffer. DPR can enhance the sustainability and reliability of water supplies via recuperating potable water from wastewater (Ghernaout and Elboughdiri, 2019).

This paper discusses the direct potable use of treated wastewater as a significant water source and presents the current case studies of direct potable use. This paper discusses and compares case studies of direct potable reuse in Namibia, South Africa, Texas and New Mexico. The case studies demonstrate a diversity of approaches and applied technologies. This paper provides useful information about DPR and current cases of DPR around the world. Also, this paper relies on existing literature about DPR, and it could help water planners and the local unities to analyze applying of DPR for solving current and future problems with water resources.

2. Circular principles in the water sector - potable water reuse

Lately, with the rise of environmental awareness, the circular principles have been applied in the water sector. Public water and sanitation utilities can become engines for the circular economy (IWA, 2016). To achieve circular economy goals and to close loops, the technological approach is focused on applying technical innovations for reducing water consumption, water reuse, and wastewater recycling, to keep the highest value of water, generate new inputs and material, while also optimizing production costs (UNESCO and UNESCO i-WSSM, 2020). Municipal wastewater and industrial wastewater are potential sources for wastewater recovery and reuse. Water reuse encompasses various activities with its unique characteristics based on the source water and the end-use. Figure 1 presents how different types of water reuse projects can be integrated into the urban water cycle (EPA, 2021a). Potable water reuse, water desalination, imported water, and non-potable water reuse are only some options for consideration of water reuse for many purposes (EPA, 2018a). Generally, potable water reuse in the practice involves the planned use of treated municipal wastewater for augmenting drinking water supplies (EPA, 2012). Proponents of potable water reuse and owners of water and sanitation utilities are exploring and trying to implement key strategies to accelerate the mainstreaming of potable water reuse. Also, many utilities are considering or planning to use advanced treated water as an alternative water supply for potable reuse. Potable reuse refers to recycled water people can use and drink. Currently, municipal wastewater is treated in wastewater facilities to a level where it is safe to discharge it to the environment. New principles in the water sector refer to further additional treatment of treated wastewater and its use for various applications or as a use of drinking water (WateReuse, 2021). In general, potable reuse is the process of taking treated wastewater from a wastewater treatment facility and purifying it further with advanced technologies (Water Research Foundation, 2021). Potable water reuse projects imply the use of more intensive additional treatment requirements, control, and monitoring.

2.1. Indirect potable use and direct potable use

Advanced wastewater treatment is conducted after primary, secondary, and tertiary (conventional) treatment, and it is focused on the removal of organic carbon compounds, nutrients, metals, suspended solids, and pathogens. Treated water may be recycled for non-potable uses (such as gray water and irrigation) or reused via IPR or DPR as drinking water (Noibi et al., 2020). IPR relies on blending treated wastewater with other natural water sources (river, lake, etc.) via environmental buffer over enough time. Therefore, facilities must have access to environmental buffers such as a surface water reservoir, massive storage tank, and aquifer. The use of environmental buffer presents the main difference between IPR and DPR (Eden et al., 2016), figure 2.

Table 1 presents individual processes used in advanced wastewater treatment facilities for potable water treatment (IPR and DPR). Processes are combined depending on the location of facilities, available technologies, requirements, etc., to achieve water quality appropriate for potable reuse. Facilities for advanced wastewater treatment have five objectives: removing suspended solids, reducing dissolved chemicals, disinfection, water stabilization, and producing water with good quality (EPA, 2018).

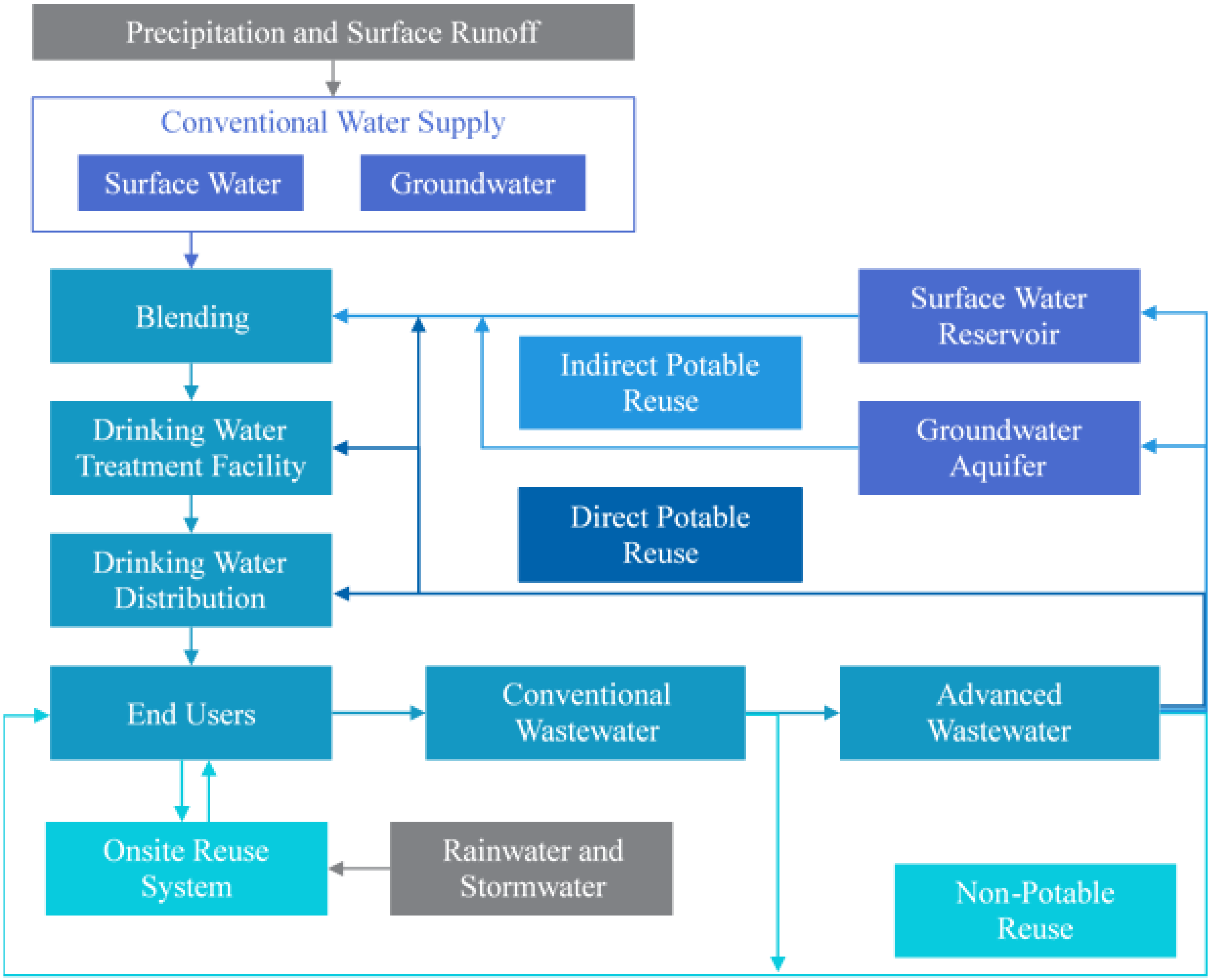

Figure 1. Examples of integrating water reuse into the urban water cycle (EPA, 2021a)

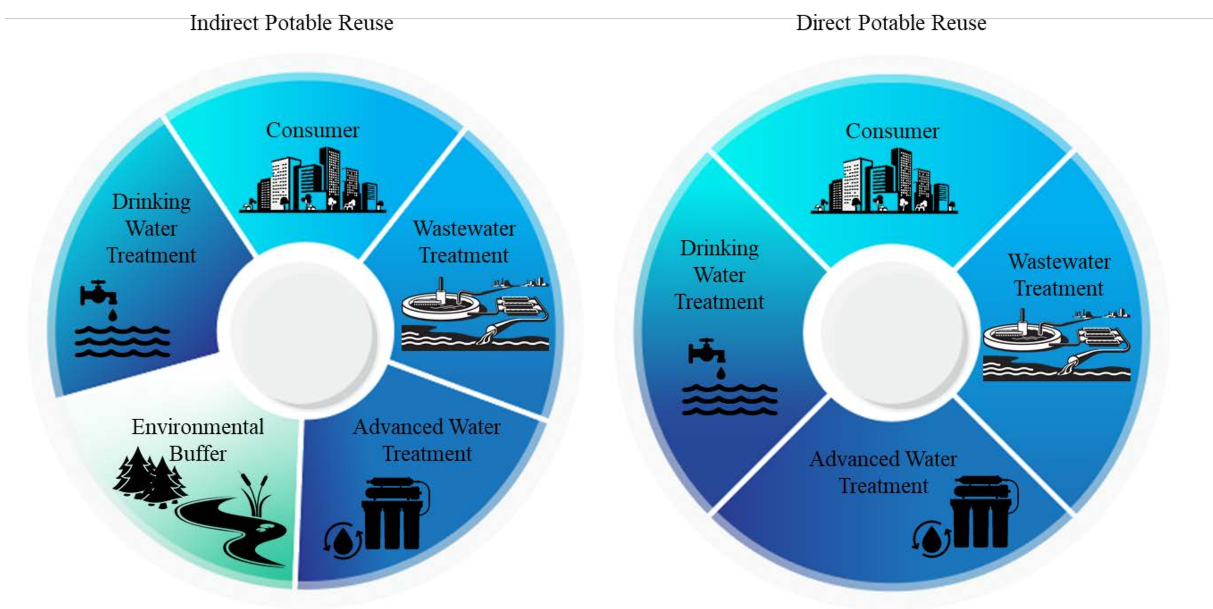

Figure 2. Illustrative representation of the difference between IPR and DPR

Table 1
Overall treatment objectives and corresponding unit processes (EPA, 2018)

Treatment objectives	Unit processes
Removal of Suspended Solids	Coagulation Flocculation Sedimentation Media filtration Microfiltration (MF)
Reducing the Concentration of Dissolved Chemicals	Reverse osmosis (RO) Electrodialysis Electrodialysis reversal Nanofiltration (NF) Granular activated carbon (GAC) Ion exchange Biologically Active Filtration (BAF)
Disinfection and Removal of Trace Organic Compounds	Ultraviolet disinfection (UV) Chlorine/chloramines Peracetic acid Pasteurization Ozone Chlorine dioxide Advanced oxidation processes (AOP)
Stabilization	Sodium hydroxide Lime stabilization Calcium chloride Blending
Aesthetics (taste, odor, and color control)	O_3/Biologically Activated Carbon (BAC)MF/RO

When evaluating the policy of wastewater recycling and reuse, it is helpful to consider what is achievable from a technology standpoint (Freedman and Colin, 2015). Figure 3 illustrates how selected technologies for IPR and DPR may be deployed as a function of water recovery needs and water quality. Table 2 compares the IPR and DPR.

Today, many utilities are transitioning to DPR (Steinle-Darling et al., 2016). The DPR refers to the additional treatment of purified water derived from municipal wastewater after extensive treatment to assure that strict water quality requirements are met at all times (EPA, 2012). There are two types of DPR. Treated water is introduced into the raw water supply upstream of a drinking water treatment facility (first type), and treated water is introduced directly into a potable water supply distribution system (second type) (WateReuse, 2020), Figure 4.

In DPR, the reclaimed water is treated to drinking water standards and then diluted with the drinking water in the water network. In other terms, implementation of DPR requires reliance on the applied technology to produce water that is safe and acceptable to consume. That is possible due to the technological progress, however, there are significant barriers that exist concerning consumer acceptance and regulations. A key part of a DPR system is the ability to provide high-quality water reliably all the time (Leverenz et al., 2011).

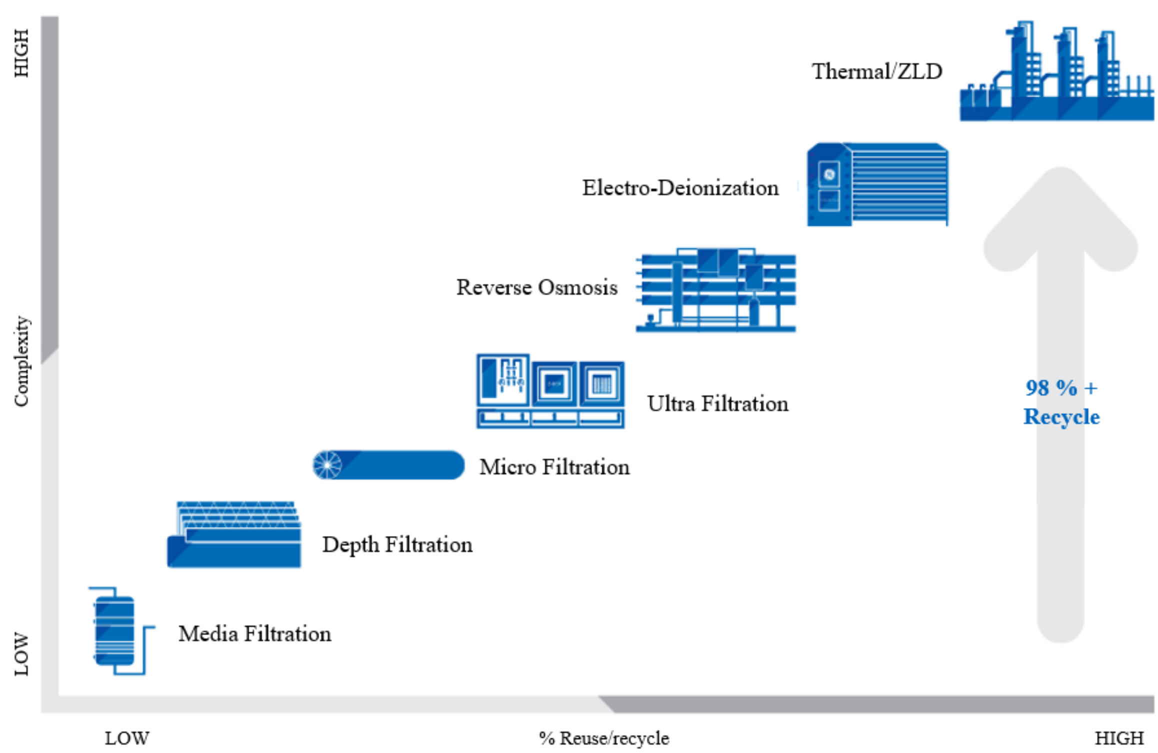

Figure 3. Reuse technology spectrum (Freedman and Colin, 2015)

Table 2
Comparison of IPR and DPR (Aravinthan, 2005; EPA, 2018)

Description	IPR	DPR
Treatment	Multiple barrier treatment before surface augmentation or aquifer injection	Demands extensive treatment of the wastewater prior to reintroduction directly to the drinking water facility.
Practicality	IPR can be impractical if the environmental buffer is not suitable	DPR requires a higher level of monitoring and treatment complexity, although elimination of an environmental buffer provides a higher level of control over the water
Treatments requirements	Several states have regulations or guidelines for IPR treatment requirements	There may be no difference in the treatment objectives between IPR and DPR; however, the level of process monitoring and control, and the total level of treatment may be more complex for DPR due to the absence of an environmental buffer
Contaminants	Fewer contaminants undergo dilution, mixing, and natural treatment in the receiving body before abstraction into the drinking water facility	Certain chemicals tend to concentrate over time when water is repeatedly recycled
Water quality	Depending on site-specific conditions, environmental buffers have the potential to either enhance or degrade water quality	DPR provides a high level of control; but, the process monitoring and control may be more complicated than IPR
Water rights	Water rights issues can complicate IPR potential	Water rights issues can complicate DPR potential
Community reactions Public perception	Newly introduced IPR, though highly treated than unplanned discharge, tends to upset the communities	Very negative
Discharge	Wastewater effluent is normally discharged upstream	No discharge outside
Costs	Environmental buffers can incur significant costs to protect, maintain, operate, and monitor.	DPR may require a higher level of operator training and may involve additional treatment steps beyond IPR
Regulations	Several states in the USA have regulations or guidelines governing IPR	DPR facilities are currently considered on a case-by-case basis, and to date, no states have formal regulations or guidelines governing DPR

Figure 4. Two types of DPR (WateReuse, 2020)

The DPR systems have their advantages and disadvantages. Some of the advantages and disadvantages are listed in Table 3. The advantage of the DPR system is that the facility for wastewater treatment and the facility for advanced water treatment are located at one place or in the immediate vicinity, which directly affects the reduction of operating costs, water transport costs, and energy needs. Water is transported over short distances so that a small number of external factors can affect its transport. The lack of these systems is based on public outrage, the absence of law, and the constant need to monitor water quality and safety.

Table 3
Advantages and disadvantages of DPR (National Research Council, 2012; ATSE, 2013)

Advantages	Disadvantages
Water security: conserves drinking water and contributes to a sustainable water supply; Environment benefits: reduces the amount of treated wastewater going into local waterways, uses an otherwise resource, reduces energy requirements, reduces carbon footprint, and reduces chemical consumption and/or waste production; Infrastructure: improved flexibility of water supply, cost savings; Water quality: maintenance of high water quality produced by advanced treatment processes/improved water quality control.	Regulatory framework: lack of political will, lack of regulatory framework and/or regulatory competency or regulatory acceptance; Industry: lack of industry competency; Water quality: poor water quality, water quality incident and loss of 'time to react', loss of advantage from using environmental buffer as a means of transporting or distributing water; Security and monitoring: the constant need for real-time monitoring; Community: safety concerns, resentment; Costs: high costs associated with DPR.

3. Review of DPR systems

This paper presents some DPR systems that are currently in operation and/or under construction. All DPR systems are unique because they apply different processes of additional treatment of treated wastewater and use various technologies for drinking water production. Figure 5 presents DPR systems that are currently in operation and/or under construction around the world.

3.1. Africa

3.1.1. *Goreangab reclamation plant, Windhoek, Namibia*

Namibia is one of the most arid countries in the world. In Namibia, heat causes about 83 % of rainwater to evaporate, and the ground only absorbs about 1 % of rainwater (Veolia, 2021). The water supply of Windhoek, the city in Namibia, depends on boreholes and three dams located 60 and 200 km away. Without nearby water sources and due to water shortages, the city has sought alternative solutions to secure its water supply. In 1968, it was decided to design and construct the facility for treated wastewater recycling for drinking purposes. Since 1969 (when the facility was constructed), Windhoek has reused treated wastewater to satisfy drinking needs (City of Windhoek, 2021). Today this plant provides over a quarter of the total water supply, and for 55 years, people have been drinking reused treated wastewater. This is the first city in the world that started to use DPR and reuse its domestic wastewater for drinking purposes. DPR plant uses technologies that mimic natural water cycles to eliminate all possible health hazards and to ensure drinking water quality. Domestic effluents are first treated in the City wastewater treatment plant. After that, the treated wastewater passes into the DPR plant. The multiple barrier technique reproduces the natural water cycle in several phases: pre-ozonation, coagulation/flocculation, floatation, sand filtration, ozonation, filtration, activated carbon adsorption, ultrafiltration, and chlorination (City of Windhoek, 2021). The resulting potable water is subjected to permanent quality controls, and to date, there have been no negative health impacts connected with the consumption of recycled water. In total, it takes around 10 hours from the moment wastewater arrives at the treatment plant to the moment it leaves as drinking water. The plant was designed to treat 27,000 m^3, however, today, during the peak hours, it treats about 41,000 m^3/day (Maquet, 2020). The DPR plants produce 35 % (350,000 inhabitants) of the water for Windhoek. Today Windhoek DPR plant has become a global benchmark and a model for innovative and sustainable water management.

3.1.2. *Beaufort West, Karoo, Durban, South Africa*

Beaufort West Municipality is located in central Karoo, in South Africa. It is one of the driest parts of South Africa and approximately has 51,000 residents (Western Cape Government, 2020). DPR plant was built in 2010 when the town's main water supply dried (the Gamka Dam). The plant uses the next steps for treatment: pre-chlorination, sedimentation, intermediate chlorination, rapid sand filtration, ultrafiltration, reversed osmosis, advanced oxidation process, and final chlorination. The reclaimed water is blended with the borehole and treated dam water in a storage tank before being pumped into the distribution system. The construction of the plant cost about 1.37 million euros, and the plant became operational at the beginning of 2011 (Visser, 2021). Although the Gamka Dam was refilled and reached 100 % capacity by September, the DPR plant continued operating.

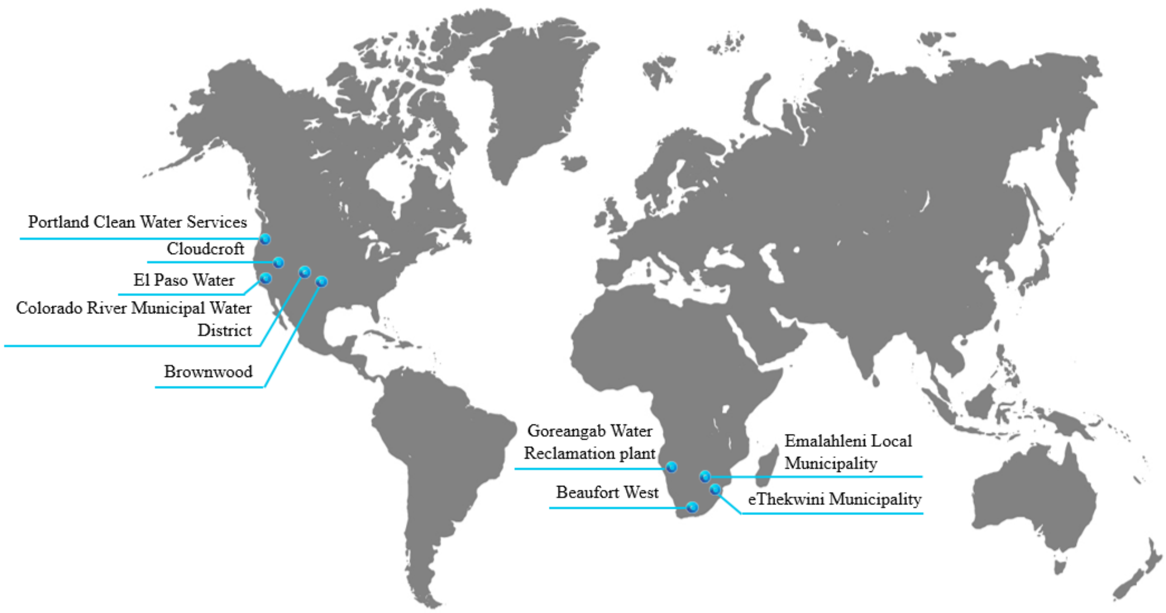

Figure 5. Planned and constructed DPR systems over the world (EPA, 2018)

3.1.3. *eThekwini, Durban, South Africa*

eThekwini Municipality has about 3.6 million inhabitants (Municipalities of South Africa, 2021), it has an industrial zone (Toyota Motor Corporation), and it is the second-largest municipality in the Republic of South Africa (The official website of the eThekwini Municipality, 2021). Because of the economy and population growth, water demands increase every year. In preparation for the shortage in 2019, eThekwini Municipality started planning two wastewater reclaimed water projects for drinking water (Japan International Cooperation Agency, 2016). The treatment process consists of the next steps: flocculation, ultrafiltration, reverse osmosis, stabilization, and ultraviolet disinfection. The plant currently purifies 30 m^3/day to potable quality (Direct Water Reuse in eThekwini, 2021). To maintain the proper level of water quality, the DPR plant is fitted with online instrumentation for constant monitoring of water quality.

3.1.4. *Emalahleni Local Municipality*

Emalahleni Local Municipality is located in the Highveld region, has an extremely varied climate, and is situated on the western side of Mpumalanga province. Emalahleni Local Municipality is a water-stressed mining town and faces a challenge of ever-growing water demand. The main source of surface water supply to the municipality is the Olifants River. This river supplies more than 70 % of municipal water provision capacity.

Direct reuse of treated mine water for domestic purposes has increased over the last decade. Emalahleni Water Reclamation Plant, owned and operated by Anglo American Thermal Coal, uses advanced treatment technology and disinfection to supply drinking water to the Emalahleni Local Municipality (Water research commission, 2013).

3.2. The United States

In the past decade, several major DPR projects were implemented in Texas: the Colorado River Municipal Water District (2013), and the City of Wichita Falls (2014). Moreover, El Paso Water Utilities conducted pilot-scale testing for an advanced water purification facility (2016), and Brownwood received a building permit.

3.2.1. *The Colorado River Municipal Water District, Big Spring, Texas*

This facility is one of two DPR plants currently in operation in Texas to provide a necessary capacity for water supplies in the face of drought conditions. The Colorado River Municipal Water District (CRMWD) constructed the nation's first DPR plant to reclaim and clean previously used water for municipal use. It was the first facility of its kind in the country. The plant treats tertiary effluent from the neighboring City of Big Spring Wastewater Treatment Plant with a combination of microfiltration, reverse osmosis, and ultraviolet disinfection (EPA, 2016). The water is then added to a raw water pipeline. The mixed water (50 percent recycled, 50 percent raw water) is distributed to five water treatment plants where water is treated again using conventional drinking water cleaning techniques in the region that serve 250,000 people (CRMWD, 2021). The treatment process has proven highly effective in removing contaminants, cleaning the water to drinking level quality. The DPR plant started operating in May 2013, and the construction of the plant cost about 12 million euros (CRMWD, 2021). The plant can produce just under 9000 m^3/day of advanced-treated water.

3.2.2. *The advanced water purification facility, El Paso, Texas*

Drought has always been a challenge for the desert community of El Paso, Texas. Water utility serves nearly 685,500 people (World Population Review, 2021). With an average total rainfall of about 0.23 meters a year and a drought at least once every decade, there is awareness of water scarcity among residents of El Paso. Because of that, the advanced water purification facility (DPR plant) was designed. The pilot facility was designed to treat the effluent from the local wastewater treatment plant (Guerrero, 2016) through a four-step technology process: membrane technology, reverse osmosis, ultraviolet disinfection with advanced oxidation, and granular activated carbon filtration (El Paso Water, 2021). About thousands of water samples from the pilot facility were analyzed, and the results showed that the purified water met required standards.

The facility will treat up to 27,300 m^3/day. It is expected that this project will be completed in near future. The project of the DPR plant is estimated to cost around 95 million euros to 130 million euros. As the first large US city to embrace DPR, El Paso would contribute about 4 % of potable reuse capacity additions over the next five years. DPR project is an example for the nation and the world of how a forward-thinking utility can use the latest technology to create a safe, sustainable, and locally controlled water supply to sustain and grow a community in an increasingly arid climate. Currently, about 30 percent of the facility is constructed.

3.2.3. *Wichita Falls, Texas*

In 2014, the City of Wichita Falls started its DPR project to provide the required amount of water. This project was temporary until a longer-term IPR project was completed. This project involved the reconfiguration of two existing water treatment plants. One of them was a conventional surface water treatment plant (coagulation, softening, flocculation, clarification, filtration, and chloramine disinfection), and the other one was designed to treat brackish surface water and consisted of conventional surface water treatment (i.e., disinfection, coagulation, flocculation, and clarification) followed by microfiltration and reverse osmosis (Steinle-Darling et al., 2016). The DPR plant was treating about 19,000 m^3/day effluent (Steinle-Darling, 2015). The process involved a seven-step process for treating water. First, the water was treated in MF/RO plant, and after that, the water was blended with 50 % existing surface water supplies and then treated in the conventional surface water treatment plant (Aquino and Brears, 2021). The DPR project's overarching goal was to supply 50 % of the city's needed water resources (Freese and Nichols, 2016).

Due to the record rainfall in 2015, the water reservoirs were returned to 100 % capacity, and the city decided to shut down the DPR plant and transit to the IPR as it was previously planned. In late 2015, the DPR pipeline was disassembled and repositioned to the wastewater treatment plant for IPR operations (Nix et al., 2021).

3.2.4. Brownwood, Texas

The Brownwood is in western Texas, and this area began experiencing drought in 2007. By 2011 severe water rationing and mandatory conservation were enforced, making the public acutely aware of water scarcity. Water utility serves a population of 18,679 (Data USA, 2021). In 2012, Brownwood became the first city in Texas to obtain approval for DPR (Scruggs et al., 2020). Although the project was approved in December 2012, it was put on hold due to sufficient spring rainfall in 2015 to satisfywater requirements.

3.2.5. *Clean Water Services, Portland*

Clean Water Services produced a batch of high purity water that far exceeded safe drinking water standards and provided it to local brewers to make beer. The treatment facility treats more than 0.09 billion m^3 of water. Water quality nearly meets drinking water standards. Most of the cleaned water is released into the Tualatin River, while some (more than 0.24 million m^3) is reused for irrigation, and some is used in the beer industry (Clean Water Services, 2021).

3.2.6. *Cloudcroft, New Mexico*

Cloudcroft is located in the mountains of southern New Mexico. The population often more than doubles on weekends due to tourism. Drought conditions have reduced the supply to below demand, and exploration for additional groundwater found no new supplies, and because of that, in 2006, Cloudcroft decided to implement DPR. Construction of the DPR facilities began in 2009 (Scruggs et al., 2020). DPR scheme has been developed, and it (379 m^3/day) consists of an MBR followed by RO and AOP. The reclaimed water is then blended with ground and spring water (>51 %) and stored in an engineered storage buffer. Further, the water is treated by an advanced water purification system (UF, UV disinfection, GAC, and chlorination) (Lahnsteiner et al., 2018).

3.3. Comparison of DPR projects and discussion

Table 4 provides an overview of DPR projects and includes information concerning the location, year of installation, current status, type of water reclamation plant (WRP) inlet (source water), reclamation plant capacity, blending with other water sources, and the additional treatment of the blended water. Figure 6 provides an overview of applied technologies in DPR plants.

Technologies used in the listed DPR projects are similar. It is crucial to treat treated wastewater to the desired quality for effective and safe reuse for drinking purposes. The efficacy of the treatment processes is also enhanced, and the water quality is guaranteed with the development in technology. Efficient treatment technology for the treatment of treated wastewater increases the public acceptance of reclaimed water. The water is therefore thoroughly processed to remove all particles, pollutants, and pathogens. The degree of treatment depends on the level of treated wastewater, and because of that DPR plants use different treatment options. The degree of the treatment is directly related to the cost and intended use of water. That means that the higher quality of water requires higher treatment costs. Comparing to regular water supply plans in cities, planning reuse of wastewater for drinking use in cities make additional costs, which can result in the fact that reclaimed water is more expensive.

Table 4
Comparison of DPR project (Gisclon et al., 2002; Hutton et al., 2009; EPA, 2018; Lahnsteiner et al., 2018)

Facility Name/ Project Name	Location	Year of installation	Status	water reclamation plant inlet	water reclamation plant, Q (m^3/day)	Blending - reclaimed water/ 'natural water'(%)	Additional treatment
Goreangab Water Reclamation plant	Namibia Windhoek	1969 expanded in 2002	Operational	Secondary domestic effluent	27,000 - 41,000	25/75b (treated dam water þ groundwater); Pipe-to-pipe blending in the distribution network	None
Beaufort West	South Africa Western Cape province	2011	Built	Secondary municipal effluent	2,000	20/80 (treated dam water þ ground water); max. 30% of reclaimed water; blending in a storage tank	None
eThekwini Municipality	South Africa Mpumalanga province	2001	Operational	Treated domestic and industrial effluent	47,500	-	-
Emalahleni Local Municipality	South Africa	2007	Operational	Mine water	-	Water is sent to nearby Anglo American mines and to the eMalahleni Local Municipality.	-
Colorado River Municipal Water District (Big Springs)	USA Texas	2013	Operational	Disinfected tertiary municipal effluent	7,600	50/50 (treated water/raw water)	Conventional WTP
El Paso – Advanced Water Purification Facility	USA Texas	Future	Undergoing regulatory approval	Tertiary municipal effluent	27,300	Straight to distribution system	None
Wichita Falls	USA Texas	2014-2015	Closed	Secondary municipal effluent	19,000	50/50 (untreated lake water); blending in a splitter box	Conventional WTP
Brownwood	USA Texas		Construction approval	Tertiary municipal effluent	5,700	Blending in the distribution system with treated lake water	None
Cloudcroft	USA New Mexico	2016	Built but delayed	Secondary effluent from MBR	379	49/51 (spring/well water); blending in an engineered storage buffer	Advanced WTP (UF, UV, GAC, NaOCl)

Also, depending on the local circumstances (location, domestic water demands, available water, climate changes, etc.) DPR is not always a possibility and good option. Depending on factors like wastewater quantity and quality, type of treatment and distribution system, cost, public awareness, etc., there are several feasible options for the reuse of treated wastewater. City planners should check which option for water reuse is possible in the city. The DPR refers to designing the water scheme where the aim is to reuse treated wastewater for drinking purposes. DPR consists of proper treatment of wastewater and overall optimization of treatment and distribution scheme for reclamation and reuse of water. People understand the environmental and economic importance of reusing treated wastewater, but also have some concerns that could affect their acceptance of the DPR scheme. Concerns are related to the quality of the drinking water, health reasons, and lack of trust in the treatment process. With the shortage of freshwater availability, growing populations, and increasing water demands, the circular approaches towards the use and reuse of water have emerged as a priority. The circular economy approach of reusing treated wastewater has potential benefits for people, such as that the reused wastewater can provide a reliable water source for drinking purposes.

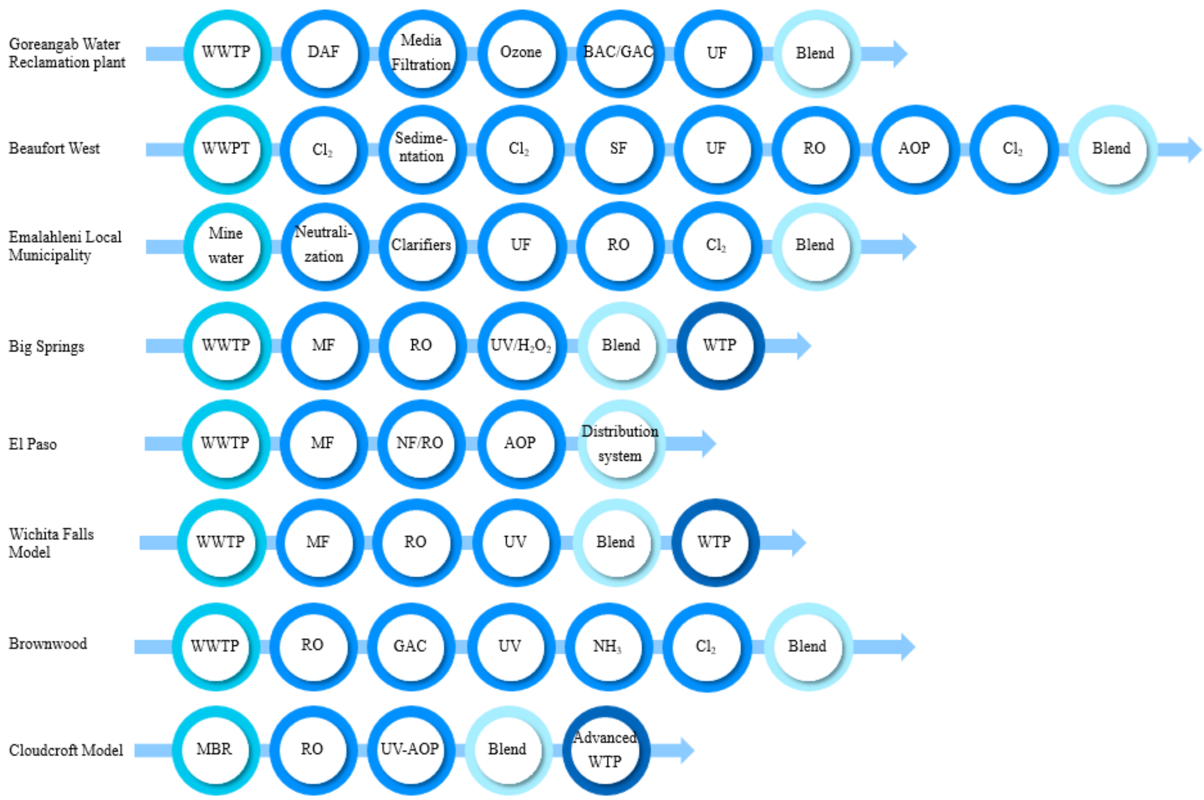

Figure 6. Applied technologies in DPR plants (Hutton et al., 2009; Lahnsteiner et al., 2018; AWWA, 2021)
AOP – advanced oxidation process, BAC – biological activated carbon filter, DAF - dissolved air flotation, GAC - granular activated carbon filter, MBR – membrane bioreactor, MF – microfiltration, NF – nanofiltration, RO – reverse osmosis, SF – sand filtration, UF – ultrafiltration, UV – ultraviolet disinfection, WTP – water treatment plan, WWTP – wastewater treatment plant

4. Conclusion

Climate change, combined with increasing urban growth and existing water stress, creates additional strain to already limited water supplies and compounding water availability challenges. Water is a resource under pressure, and the first response to reduce that pressure is to optimize consumption. Today that is not enough. Reduction of the pressure is possible if the reduction of water consumption is combined with the establishment of a closed circular water loop through potable water reuse. Recycled wastewater is increasingly used to meet increasing water demand and to provide more reliable water supplies. DPR is a time, resource, and money-intensive process, but it is already widespread in many cities across the globe. This paper offers a review of successful examples of the DPR projects. Residents in these cases were affected by dry conditions and water scarcity, and they understood the need to reuse wastewater for drinking purposes, notably because there were no additional water supplies. Various global studies present that, shortly, most countries will be affected by water stress and that water supplies will be reduced and, therefore, learning about DPR and presenting successful examples of DPR can help communities consider new circular and innovative programs for drinking water supply. Also, this paper presents and compares the technologies used in DPR, however, to understand the DPR, it is necessary to conduct further research on water quality before and after treatment, legislation, necessary financial resources, and public acceptance of this system.

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Budućnost reciklaže vode – Pregled primera direktne ponovne upotrebe pijaće vode

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INFORMACIJE O RADU

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Ključne reči:
Direktna ponovna upotreba vode za piće
Recikliranje vode
Otpadne vode
Voda za piće

I Z V O D

Stopa rasta stanovništva i nestašica vode su uticali na razmatranje upotrebe prečišćene otpadne vode kao potencijalnog alternativnog izvora vode za piće. Trenutno se reciklirana voda uglavnom koristi u industriji, poljoprivredi i za navodnjavanje. Danas se reciklirana voda, u određenim delovima sveta, koristi i kao voda za piće zbog ograničenih resursa. Da bi se zadovoljile buduće potrebe vodosnabdevanja, direktna ponovna upotreba pijaće vode bi se mogla uzeti u obzir kao mogući izvor vode za piće. Direktna ponovna upotreba vode za piće može poboljšati održivost i pouzdanost vodosnabdevanja. U ovom radu je analizirana ova tehnika kao kružni princip u vodosnabdevanju i, takođe, je upoređeno nekoliko uspešnih primera primene ove tehnike u Namibiji, Južnoj Africi, Teksasu i Novom Meksiku. Države koje koriste ovu metodu predstavljaju uspešne primere korišćenja otpadnih voda za formiranje održivog i pouzdanog vodosnabdevanja, što je od velikog značaja za budućnost.

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Hospital Hazardous Waste Management: Treatment, Storage and Disposal

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A B S T R A C T

Rapid population growth, industrialization, and growth of demand for raw materials for industrial and medical production result in generating a huge amount of hazardous waste. Hazardous waste is identified by its toxicity, flammability, and radioactivity characteristics. Disposing hazardous waste into the natural environment has a significant impact on health and all living things in the environment. Nowadays, numerous hospitals and industrial places generate a large amount of hazardous waste. The objective of this study is to evaluate the management system of hazardous hospital waste in Erbil city. Additionally, the focus is on hazardous hospital waste management and characterizations and situation of the waste in Erbil city as well. The generation rate of hazardous wastes from hospitals in Erbil city was collected for 12 months from 2015 to 2020. The results showed that the highest amount of medical hazardous waste was generated in 2019. Moreover, the number of onsite incineration centres should be increased to reduce the cost of storage and transportation.

1. Introduction

In recent decades, researchers have defined and classified hazardous waste as waste with chemical and physical characteristics, such as toxicity, ignitability, corrosivity, or other properties. The hazardous waste consists of household, medical, and industrial wastes. In addition, the management of hazardous wastes, including the way of disposing into the environment, is very crucial to achieve a lesser impact on human health and the natural ecosystem (Misra and Pandey, 2005). Increasing demand and consumption throughout the world and using chemicals in industries result in producing hazardous substances. 16,000 tons of hazardous waste are produced by 41 industries in Lebanon (El-Fadel et al., 2001). In China, hazardous waste was reported to have had the highest generation of 11.62 million tons in 2005 (Duan et al., 2008). Household solid wastes originate from home and may contain hazardous substances. It has been defined that such products are paints, cleaners, car batteries, e-waste, varnishes, motor oil, and pesticides (EPA, 2013). It is appraised that by 2030, developing countries will have discarded 400-700 million outdated computers. Many hazardous wastes, such as chemical photography wastes, oil wastes, battery wastes, mercury lamp wastes, electronic wastes, and heavy metal wastes with a printed circuit board (PCB), result from a large amount of trash. In some industrialised nations, household hazardous waste (HHW) may also come from municipal solid garbage. The most common recycling and recovering sectors are informal recyclers. The common safe methods in developing countries to manage hazardous waste are landfilling and incineration, however, other treatments (sterilization and microwave) have not been used. Thus, the accelerators of hazardous waste (HHW) cannot be avoided. Currently, the industry

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is sharing with the developed society waste products which are the main result of the activity of industrial countries. Increased uses of chemicals in industry produces hazardous material. Normally, the consumption trend increases the quantity of hazardous waste in the country. The way to increase material waste is to throw away the material without anticipating whether it could be hazardous waste in the environment. One way to characterize the waste as industrial is to assess its potential to become hazardous. The procedures that can generate this type of waste are tanning, electroplating, and use of pesticides, petroleum, and battery acids. This study illustrates the management of hospitals hazardous waste in Erbil city. In addition, the generation rate and characteristics of hospital hazardous waste, the method of treatment and storage of the waste were investigated as well.

2. Characteristics of hospital hazardous waste

According to the Environmental protection Agency (EPA), hazardous waste can be characterized as flammable, corrosive, toxic, reactive, and radioactive. Hazardous waste has the ignitability with high heat or any sources of fire as it has a flashpoint of less than 60 ºC such as alcohol, petroleum wastes, solvents, etc. (Bouis et al., 1999). The corrosively of hazardous waste causes damage and disease as it makes erosion and burns the skin. These wastes have a pH value less than 2.5 and more than 12.5 such as acidic wastewater, battery, etc. Cyanide, sulfide wastes, and TNT operations are examples of reactivity of hazardous waste. It is capable of exploding when mixed with water which produces toxic compounds. Moreover, toxic compounds such as heavy metals; arsenic, barium, benzene, chrome, etc, exhibit the toxicity characteristics of hazardous waste. In addition, another characteristic of hazardous waste is having radioactive elements. These wastes significantly originate from biomedical training and research institutes. Wastes may include radioactive elements of iodine, cobalt, and uranium (Tadesse, 2004).

2.1. Medical waste

Health and related services such as hospitals, health centres, clinics, and research institutes are sources of medical waste (Sartaj et al., 2015). It consists of of heavy metals, radioactive, genotoxic, pathological waste, chemical toxins, human blood, blood parts, waste of infection, and sharps which include syringes, knives, broken glasses, scalpels, and needles. Currently, there is no statistical information data about the medical waste in developing countries. Olukunle et al. (2015) mentioned that in some conditions medical waste quantity was estimated based on accounting for the number of beds in the hospital. The example is Dhaka, Bangladesh where about 37 tonnes of the medical products waste was recorded (Patwary et al., 2009). On the other hand, Manga, et al. (2011) argued that the medical waste had low ratio in some developing countries. Municipal solid waste (MSW) is recorded to have high ratio of medical wastes and there is no control and monitoring of the wastes. The main way to control medical waste is incineration treatment. Therefore, there ara lacks in operation treatment of medical waste in some developing countries. The consequence of pollution results from simple technology and primitive equipment.

3. Treatment and disposal of hazardous waste

Hazardous waste management is comprised of the transportation, disposal of waste, storage, handling, and possessions. Hazardous treatment happens in uncontrolled situations and irregular conditions in developing countries, and hazardous waste is exported to some developing countries by the developed countries (Thanh et al., 2010). It was recorded that the treatment of hazardous was done by the unlicensed conventional method, for example, Landfill. According to Patwary et al. (2011), the treatment of hazardous waste by authority was done with low standards or regard to the environment and technology. The examples are landfills, oil recovery, and incineration plants. The most important hazardous waste is mixed with non-hazardous material. This has influence on the environment and human lives and it creates high-risk health problem to the public and environment. This indicates that hazardous waste in developing countries needs to use a new strategy and new technology to improve the environment from hazardous materials. Modern technology, high recycling techniques and managing hazardous waste that highly affects the environment, economy, technically feasible and social standards. Hazardous waste is present in South Africa which is one of the developing countries (Olukunle et al., 2015). There are challenges in some developing countries to develop hazardous waste disposal due to regularity, financial resource, social acceptance, limited technology, and infrastructure and manpower skill. It indicates that landfill is not crucial in their society. It shows that the combustible hazard needs to be monitored and new infrastructure for the wastes do not exist. The common environmental issue such as Contamination of soil and animal threats may be a result of oils and indiscriminate or e-wastes. Healthcare facilities are mixed with water channels that are not properly cleaned. Monitoring of the environmental risks is related to the practices which have not been done due to poor technique and man skill. Industrial hazardous waste can be defined as waste that comes from sectors of the industrial and it through to the environment (Naviaa et al., 2008). Industrial hazardous waste is recognized by high toxic (chronic, extrinsic and acute), reactivity, corrosiveness and flammability. Industrial hazardous waste sources are chemical, mechanical, paper, pulp, mining, wood and cement production and important Industrial hazardous waste is contaminated oil (Thanh et al., 2010). In some countries using industrial wastevis high, for example, in Lebanon is around 3,000 - 15,000 ton/Y this is due to the lack of an environmental plan. Furthermore, there are little data collected about Industrial hazardous waste to know where and where generated and goes. Due to the fluctuation the mass manufacturing, economic, industrial process, environmental quality leads to an increase the Industrial hazardous waste. A large portion of hazardous waste is missed with non-hazardous from landfills that through to the water and make more environmental problems (Olukunle et al., 2015). Researchers have found that in origin the waste is not discrete from hazardous and non-hazardous substances. Also, non-hazardous substances are not discrete from recyclable and non-recyclable. Researchers have found that some developing countries do not have regulation which leads to hazardous waste. In addition, the separation for the rest of the wastes is easily in developing countries. This indicates that possible and urgent policies need to stimulate industry, manage society and reduce the hazardous problem.

4. Current situation of hospital hazardous waste in Erbil City

4.1 Study area and data collection

Erbil city is the capital of the Kurdistan region located at 35º 27' N to 37º 24' N Latitude and 43º 15' E to 45º 14' E longitude. The population of the city area is around 1,300,000 citizens (Khudhur and Khudhur, 2015). The solid waste generation in Erbil city varies between 0.8 to 1.4 kg per capita per day. The amount and composition of solid waste in households in Erbil city varies depending on lifestyle and members of the family. The collected solid waste from Erbil city is dumped and buried in the Kani-Qrzhala dumpsite which is far from the city centre about 15 km from the northwest (Aziz et al., 2011). Erbil landfill site at Kani-Qrzhala is opened in 2001 and it is not constructed and designed as a sanitary landfill. Since there are no facilities in the city to recycle the inorganic materials and separate components of the generated solid waste, therefore; the landfill receives all types of solid waste around 2,000 tones daily including municipal, commercial, household hazardous, industrial and final products from the incineration of medical wastes from hospitals. This study focuses on the management of hospital hazardous waste and in addition, the current study investigates the current situation, generation and treatment of hazardous waste in Erbil city. The data is collected from the Erbil Environment office (EEO). The data contains monthly generation of medical hazardous waste from various hospitals from 2015 to 2020. The wastes data include infectious waste, sharp waste, pathological waste, etc. The data was then organized using Microsoft office excel and the total annual waste generated was calculated for the year 2015 till 2020 (Appendix 1).

Hazardous waste in Erbil city significantly comes from medical waste which is followed by hospitals and industrial locations. Currently, numerous amount of hospitals are serving inside the city. These hospitals use chemicals in laboratories to treat their patients, so by the end, it will generate a huge amount of hazardous wastes which may contain heavy metals and toxic compounds. Figure 1 shows the location of hospitals in Erbil city.

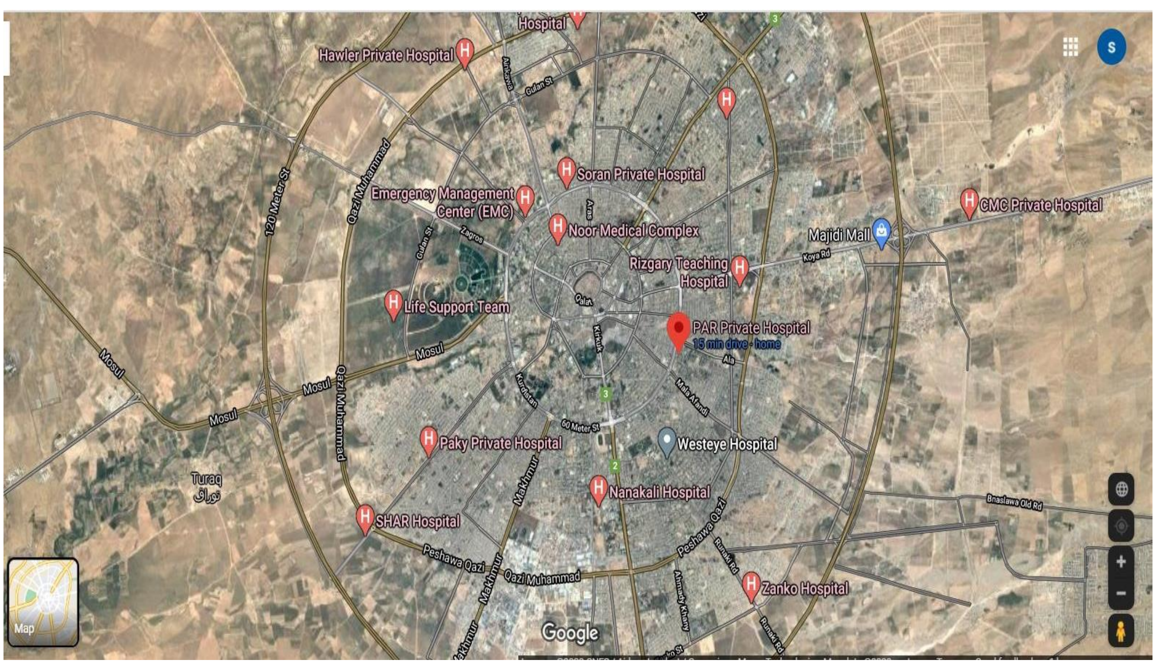


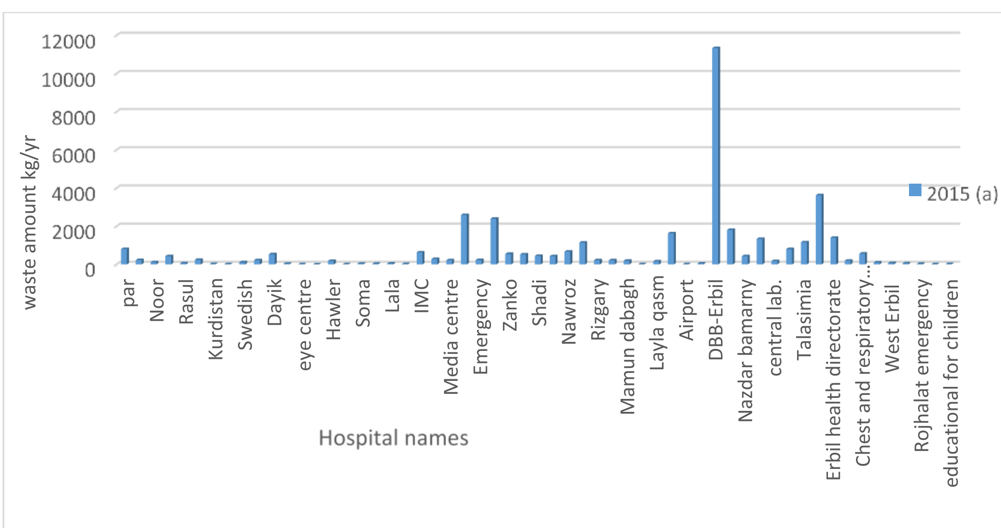
Figure 1. Location of hospitals in Erbil city

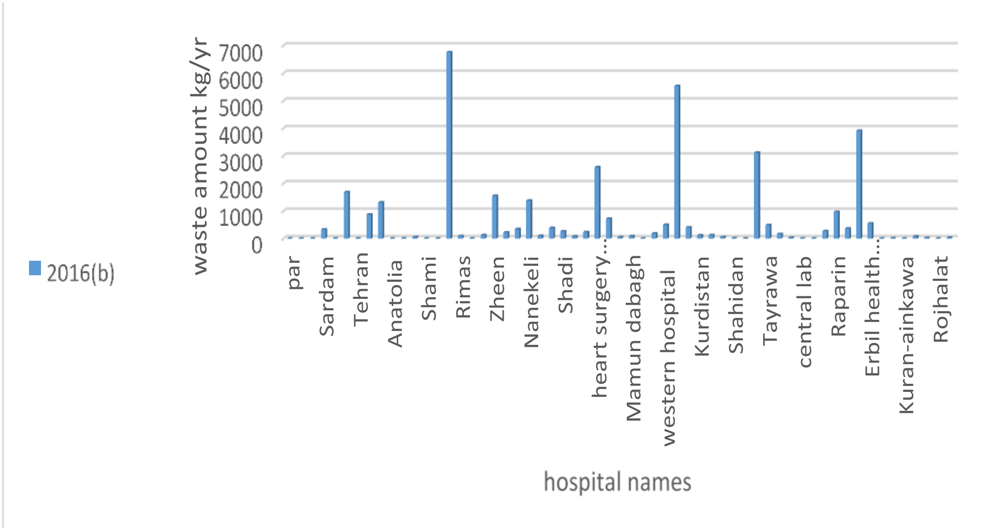
From data, the generation rate of medical wastes at hospitals for 12 months during the years 2015 till 2020 (Appendix 1). The production of medical wastes is sent to two main treatment unit plants; incineration device which is constructed at Nanekali and childbirth hospitals in Erbil city. The wastes are autoclaved and then incinerated under high temperature then the ash is collected and disposed to the Erbil landfill site near KaniQrzhala district. However, sometimes some hospitals dump their medical waste directly into landfill sites and mix it with municipal solid wastes without separation and aggregation (Figure 2).

Figure 2. Mixed solid waste and medical waste at Erbil landfill site

5. Results and Discussion

From Figure 4 shows the charts with hospital names and the amount of medical waste generated in kg/year. There are fluctuations in the amount of waste from the year 2015 to 2020. Some hospitals generate less amount of waste while some others generate more waste. In 2015 Directorate blood bank (DBB) recorded the highest value, about 12,000 kg per year of generated medical waste. While in 2016 Lala hospital recorded around 7,000 kg per year. In 2017 and 2018 blood centre hospitals generated the highest amount of medical waste around 4,000 and 3,000 kg per year respectively. In addition, Figure 4 shows that in the year 2019, the highest amount of waste was recorded from the blood centre hospital. Moreover, in 2020 the highest amount of waste was generated from industrial kidney centres which was 6,000 kg per year. The transportation of wastes from all hospitals was performed by a special truck which went to two main hospitals and collected waste to be autoclaved and incinerated by special devices then the final ash was disposed to Erbil landfill site. In 2020, the lowest amount of waste was generated, which meant that the lowest number of patients visited the hospital as mentioned by (Naemi et al., 2021). The most common process for controlling the process is called incineration, which converts solid oxidative material of combustible to material suitable for the atmosphere, for example gasses. It is changing the waste material to low harmful, noxious and bulky materials. According to Misra and Pandy, (2005 the incineration process was able to minimize the sludge material to ash remains, which could easily be used for disposal, and soluble poisonous metal oxides. (Bucătaru et al., 2021) explained that medical waste management flow should be followed by some steps starting from disposing of wastes to waste containers then storing in the designated installations after that vehicles should transport the wastes to the incineration treatment facility. The landfills which closed to burial the toxic material for example contaminated soil with hazardous material, polychlorinated biphenyls closed the landfill where the material wastes are restricted from the surrounding environment by wall, roof and floor. The rainwater has not been able to go through landfills which closed then, the amount of leachate will be very low (Lidskog, 1998).

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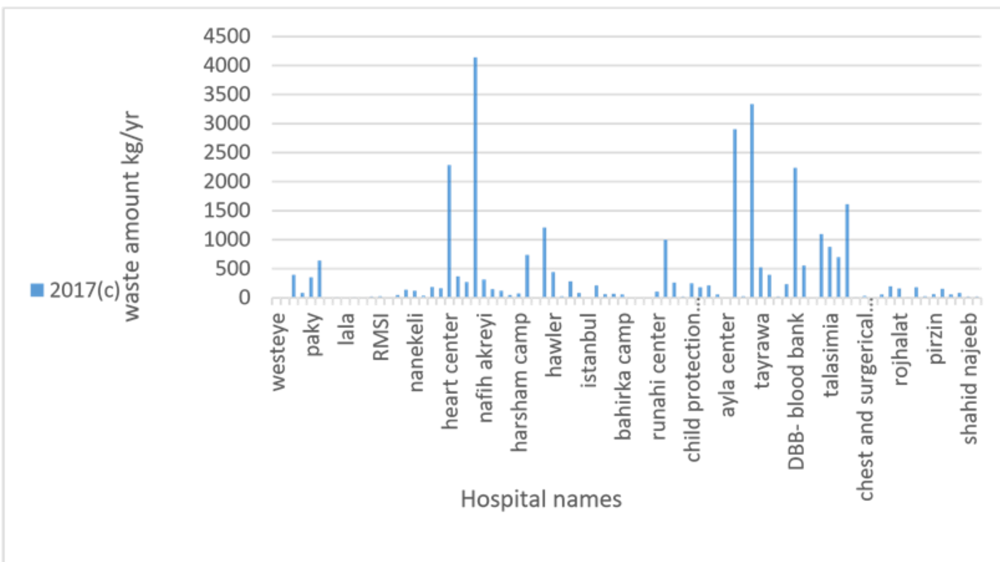
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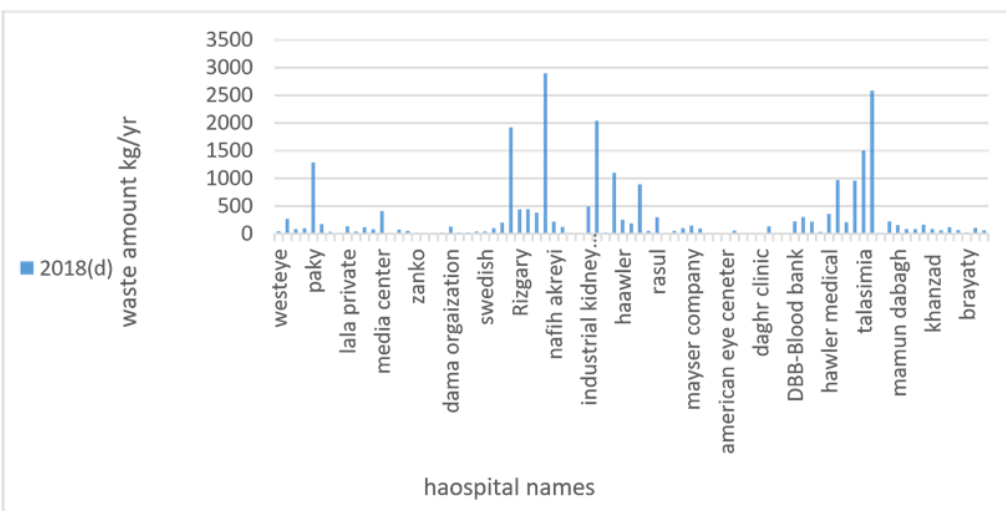
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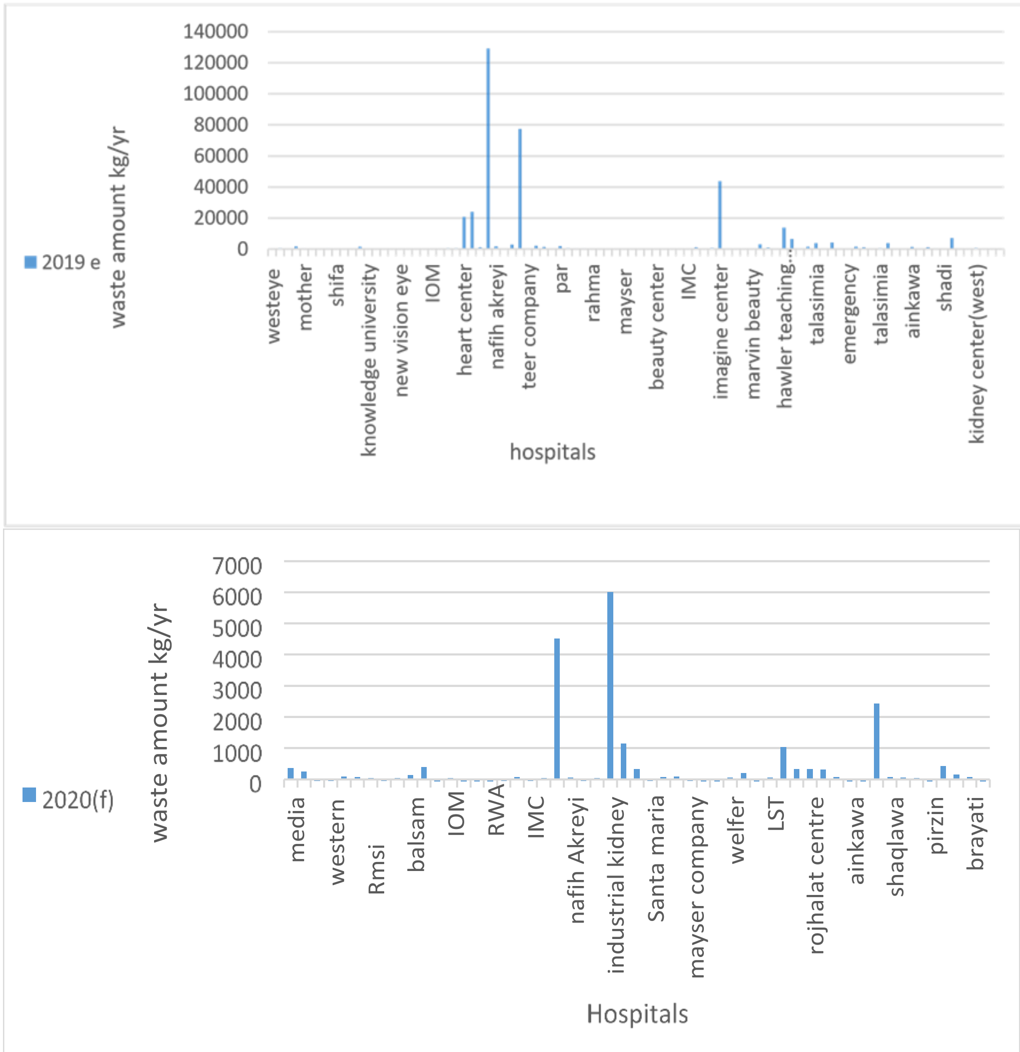

Figure 3. (a-f) The amount of medical waste generates in hospitals in Erbil city from 2015-2020 in kg/year

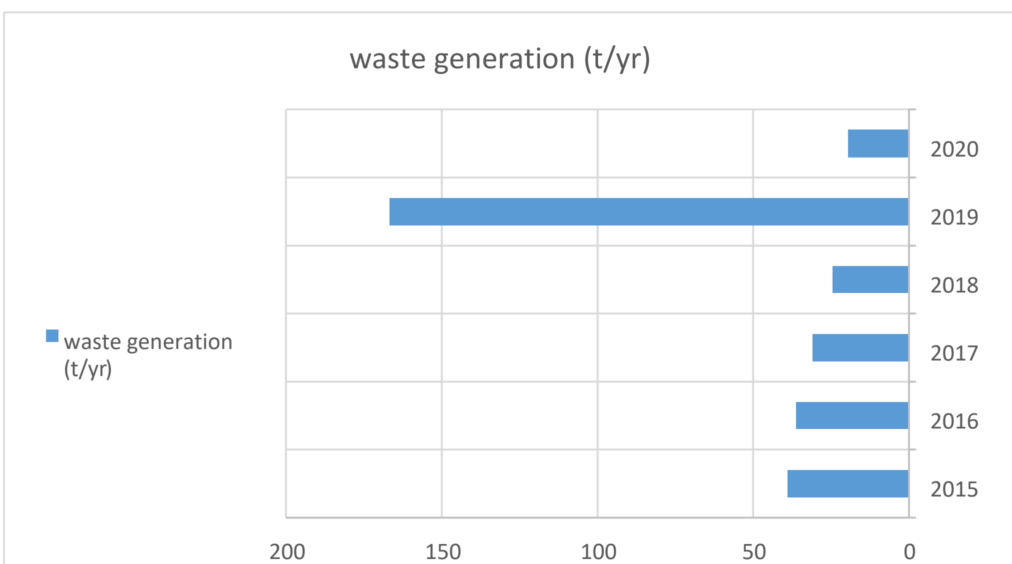

Figure 4. Yearly generation rate of hospital hazardous waste

Conclusion

This study discusses hazardous waste management with emphasis on industrial hazardous waste, medical waste, and household hazardous waste. It also identifies the current situation of hazardous waste management in Erbil city.

1. In Erbil city, due to rapid economic growth and industrialization, more than 25 hospitals have been opened and worked during the last few years. This generates a huge amount of hazardous waste with inadequate treatments.
2. Mercury compounds or polychlorinated biphenyls soils is called toxic material wastes that are buried into the landfill where there is isolated with the waste in the outer layer by wall, roof and concrete that help to protect from rain and the leached amount is very low.
3. There is a lack of a data on the quantities of the waste in the developing countries, which show the lack of awareness and capacity of hazardous waste disposal, lack of the product of hazardous waste, low penalties or incentive, stakeholder's responsibility, no clear role and infrastructure.
4. There are some challenges, such asfinancial sources, manpower skill, equipment, progressing framework, managing and monitoring of hazardous waste and testing facilities.
5. The main difficulty to the local authority to determine the objective of the long term of the hazardous waste are treatment system, disposal system, lack of the government responsibility and lack of data.
6. There is an important point that should be considered in order to succeed in hazardous waste management, and it is learning from the experience from some developed countries to combine with the context of the economic and social standard of the other developed country.
7. Reducing waste from reuse, recycling and source have influenced the minimisation of the hazardous material waste production and disposal. Also, it needs reform from the system of managing hazardous waste.

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Appendix 1
Medical hazardous waste generation from hospitals year 2015

No.	Hospital name	Jan	Feb	Mar	Ap	May	June	July	Aug	Sep	Oct	Nov	Dec	Total (2015)
		Kg	Kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg/yr
1	par	94	160	83	35		91	72	41	117	107	-	-	800
2	west eye	24	16	23	54		37	28	43	-	-	-	-	225
3	Noor	6	5	12	-		39	-	5	42	8	-	-	117
4	Sardam	78	-	30	27		135	-	-	80	-	85	-	435
5	Rasul	30	30	-	-		-	-	-	-	-	-	-	60
6	Sima	34	50	6	58		-	9	16	44	6	13	6	242
7	Kurdistan	-	24	-	-		-	-	-	-	-	-	-	24
8	Tehran	-	-	15	-		-	-	-	-	-	-	-	15
9	Swedish	-	-	-	24		-	-	15	-	25	45	-	109
10	Paki	-	-	-	-		-	-	18	-	55	68	79	220
11	Dayik	-	-	-	-		-	53	49	78	88	125	134	527
12	Anatolia	-	-	-	-		-	-	-	28	8	-	-	36
13	eye centre	-	-	-	-		-	2	-	-	11	-	-	13
14	eye teaching	-	-	-	-		-	-	4	-	-	-	-	4
15	Hawler	-	-	-	-		-	-	100	12	-	70	-	182
16	Sami	-	-	-	-		-	-	-	-	-	2	6	8
17	Soma	-	-	-	-		-	-	-	-	-	40	-	40
18	welfer	-	-	-	-		10	-	-	-	20	-	-	30
19	Lala	-	-	-	-		-	-	-	-	-	-	42	42
20	Rmsi company	-	-	-	-		-	-	-	-	-	-	22	22
21	IMC	-	-	-	-	520	50	-	-	2	-	-	-	625
22	Zheen	-	-	-	-	-	84	121	77	-	-	-	-	282
23	Media centre	-	-	-	-	-	-	-	46	85	81	-	-	212
24	Zhyan	73	89	221	984	656	40	22	50	321	110	21	-	2587
25	Emergency	22	-	-	-	33	-	-	51	-	38	88	-	232
26	Nanekeli	64	94	160	134	375	449	124	244	242	120	391	-	2397
27	Zanko	65	82	10	74	72	73	-	40	33	22	78	-	549
28	Azadi	22	27	8	20	57	14	44	35	62	36	142	55	522
29	Shadi	22	70	13	-	43	83	33	32	47	18	69	15	445
30	Mala-fandi	169	74	20	-	-	39	29	-	-	-	73	25	429
31	Nawroz	49	62	15	177	36	76	23	21	62	30	79	36	666
32	heart centre	-	222	-	-	107	31	43	192	244	82	-	220	1141

Appendix 1 continued
Medical hazardous waste generation from hospitals year 2015

33	Rizgary	-	-	27	-	50	-	-	-	42	60	42	-	221
34	Ahmed bajalan	-	-	10	-	-	80	-	-	33	27	62	-	212
35	Mamun dabagh	-	-	20	-	-	50	20	16	82	-	-	-	188
36	Family	-	-	-	-	-	-	-	-	-	-	8	-	8
37	Layla qasm	-	-	-	-	-	-	-	-	-	-	127	32	159
38	Western	-	-	-	-	39	-	-	-	87	-	-	1500	1626
39	Airport	-	-	-	-	-	-	-	-	-	-	-	10	10
40	Soran	-	-	-	-	49	-	-	-	-	-	-	-	49
41	DBB-Erbil	961	743	531	2775	3702	365	435	539	450	425	406	-	11332
42	Tayrawa	67	115	193	440	769	66	35	33	36	-	50	-	1804
43	Nazdar bamarny	20	81	258	-	-	-	-	45	30	-	-	-	434
44	Sarwaran	25	27	-	200	912	62	30	17	-	43	21	-	1337
45	central lab.	170	-	-	-	-	-	-	-	-	-	-	-	170
46	Raparin	20	-	-	572	65	95	-	3	-	12	31	-	798
47	Talasimia	44	70	17	296	344	138	92	23	53	33	47	-	1157
48	childbirth	53	-	-	1000	560	180	-	120	311	408	988	-	3620
49	Erbil health directorate	-	108	190	45	657	72	65	49	68	73	66	-	1393
50	Refugee camp	-	139	60	-	-	-	-	-	-	-	-	-	199
51	Chest and respiratory centre	-	22	-	-	522	-	-	-	21	-	-	-	565
52	Kuran-ainkawa	-	-	-	-	100	-	-	-	-	-	-	-	100
53	West Erbil	-	-	-	-	-	27	-	45	-	-	-	-	72
54	pharmacy dept.	-	-	-	-	-	-	-	-	33	-	21	-	54
55	Rojhalat emergency	-	-	-	-	-	-	-	-	-	30	-	-	30
56	doctors without borders	-	-	-	-	-	-	-	-	-	15	-	-	15
57	educational for children	-	-	-	-	-	-	-	-	-	-	21	-	21

Appendix 2

Medical hazardous waste generation from hospitals year 2016

No.	hospital names	Jan	Feb	Mar	Ap	May	june	july	Aug	sep	oct	Nov	Dec	Total (2016)
		Kg	Kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg/yr
1	par													0
2	west eye													0
3	Noor	-	-	-	-	-	-	-	-	-	-	-	-	0
4	Sardam	24	-	-	100	-	-	-	200	-	-	-	-	324
5	rasul	-	-	-	-	-	-	-	-	-	-	-	-	0
6	sima	13	-	11	6	6	42.5	1625	2	7	4	4	4	1682
7	Tehran	-	-	-	-	-	-	-	3	-	-	-	-	3
8	paki	228	-	115	60	73	40	45	65	84	40	100	28	878
9	daiyk	119	-	164	68	190	45	114	248	147	131	87	42	1310
10	Anatolia	-	-	-	-	-	-	-	-	-	-	-	-	0
11	eye centre	-	-	-	-	-	-	-	-	-	-	-	-	0
12	eye teaching	-	-	44	-	-	-	-	2	-	45	2	-	48
13	Shami	-	-	-	-	-	-	-	-	-	-	-	-	0
14	Soma	-	-	-	-	-	-	-	-	-	-	-	-	0
15	Lala	10	-	-	-	-	-	7	6750	-	-	2	-	6769
16	Rimas	-	-	4	-	-	-	90	-	-	-	-	-	94
17	Shifa	-	-	-	-	-	-	-	-	-	-	-	2	2
18	IMC	-	-	-	-	32	-	-	-	-	45	25	25	127
19	Zheen	-	-	208	-	-	-	68	195	181	392	376	130	1550
20	Hawler	-	-	31	-	25	-	30	25	20	-	30	65	226
21	Emergency	35	-	-	80	50	50	20	-	15	14	15	68	347
22	Nanekeli	250	-	353	200	88	47	80	90	70	75	75	50	1378
23	Zanko	23	-	-	-	28	45	-	-	-	-	-	-	96
24	Azadi	60	-	55	30	-	25	-	-	80	65	30	40	385
25	Shadi	28	-	12	10	50	45	20	29	19	10	32	10	265
26	mala-fandi	27	-	15	12	22	-	-	-	-	-	-	-	76
27	Newroz	12	-	22	36	7	40	10	16	33	15	24	18	233
28	heart surgery centre	278	-	330	352	249	200	130	281	115	391	240	24	2590
29	Rizgary	15	-	166	-	305	32	20	60	25	40	30	30	723
30	Mohammed bajalan	-	-	25	-	-	-	10	15	-	-	-	-	50
31	Mamun dabagh	22	-	-	20	25	-	-	-	-	-	20	-	87
32	family	-	-	-	-	-	-	-	-	-	-	-	-	0
33	Layla Qasim	31	-	-	14	49	21	6	26	24	15	-	-	186
34	western hospital	-	-	-	-	-	-	-	-	-	-	-	500	500

Appendix 2 continued

Medical hazardous waste generation from hospitals year 2016

35	blood centre	266	-	405	710	542	545	325	585	385	540	650	587	5540
36	nafih Akreyi	12	-	17	24	62	35	29	25	36	66	40	60	406
37	Kurdistan	-	-	-	6	17	26	9	422	4	25	18	16	121
38	Airport	-	-	-	-	30	23	-	53	8	-	11	-	125
39	Shakra	-	-	-	-	55	-	-	-	-	-	-	-	55
40	Shahidan	-	-	-	-	-	-	-	-	-	10	-	-	10
41	centre of skin	-	-	-	-	-	-	-	-	-	-	4	-	4
42	DBB-blood bank	-	-	502	-	465	-	249	386	435	399	485	197	3118
43	Tayrawa	-	-	11	-	261	-	53	18	14	94	40	-	491
44	Nazdar bamarni	-	-	-	-	33	-	26	22	-	72	-	17	170
45	sarwaran	-	-	-	-	23	-	-	8	-	-	-	-	31
46	central lab	-	-	-	-	-	-	-	-	-	-	-	-	0
47	medical centre	-	-	-	-	-	-	-	-	-	-	-	-	0
48	zhyan	-	-	21	-	50	-	29	17	24	24	60	48	273
49	Raparin	-	-	-	-	-	-	-	25	-	165	350	430	970
50	talasimia	-	-	-	-	96	-	60	32	25	-	80	77	370
51	childbirth	-	-	367	-	697	-	641	48	608	531	629	393	3914
52	Erbil health directorate	-	-	9	-	273	-	42	27	20	72	40	67	550
53	Refugee camp	-	-	-	-	-	-	-	-	-	-	-	-	0
54	Chest and respiratory centre	-	-	-	-	-	-	-	12	-	-	-	-	12
55	Kuran-ainkawa	-	-	-	-	-	-	-	-	-	-	-	-	0
56	emergency	-	-	4	-	37	-	-	-	-	-	-	35	76
57	psychological	-	-	-	-	-	-	-	-	-	-	20	-	20
58	Rojhalat	-	-	-	-	-	-	-	-	-	-	-	-	0
59	Ministry of health	-	-	-	-	17	-	-	-	-	-	-	14	31

Appendix 3

Medical hazardous waste generation from hospitals year 2017

No.	Hospital name	Jan	Feb	Mar	Ap	May	june	july	Aug	sep	oct	Nov	Dec	Total (2017)
		Kg	Kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg/yr
1	westeye													0
2	noor	-	-	-	-	-	-	-	-	-	-			0
3	sardam	-	-	153	-	-	-	-	122	43	-	42	37	397
4	sima	5	2	6	5	4	-	8	20	12	-	13	11	86
5	paky	-	20	50	-	70	-	-	76	44	-	36	54	350
6	mother	80	60	151	112	72	-	49	27	11	-	45	32	639
7	eye centre	-	-	5	-	-	-	-	-	-	-	-	-	5
8	eye teaching	-	2	-	-	2	-	-	4	2	-	-	4	13
9	Lala	-	-	-	-	-	-	-	-	-	-	-	5	5
10	Shifa	-	-	-	6	-	-	7	-	4	-	-	4	17
11	Marvin	-	-	-	2	-	-	-	-	-	-	-	-	2
12	Kurdistan	-	-	-	-	-	-	18	-	-	-	-	-	18
13	RMSI	-	-	-	-	-	-	25	-	-	-	-	-	25
14	SHAR	-	-	-	-	-	-	-	-	-	-	-	5	5
15	media centre	-	-	-	-	-	-	-	-	-	-	30	18	48
16	emergency	23	60	-	-	-	-	-	-	-	53	-	-	136
17	nanekeli	29	85	5	-	-	-	-	-	-	-	-	-	119
18	Azadi	25	-	10	-	-	-	-	-	-	-	-	-	35
19	shadi	26	10	75	15	-	-	10	24	24	-	-	-	184
20	newroz	18	8	36	-	-	-	35	50	16	-	-	-	163
21	heart centre	255	470	320	161	317	-	-	224	128	198	213	-	2286
22	Rizgary	50	45	42	135	30	-	30	-	-	30	6	-	368
23	Layla Qasim	28	20	40	40	-	-	80	17	7	-	40	-	272
24	blood centre	791	508	643	541	607	-	345	-	-	242	463	-	4140
25	nafih akreyi	23	16	20	11	26	-	18	83	45	55	20	-	317
26	airport	29	40	-	-	-	-	80	-	-	-	-	-	149
27	Khazar	-	85	35	-	-	-	-	-	-	-	-	-	120
28	shahidan	-	-	45	-	-	-	-	-	-	-	-	-	45
29	harsham camp	-	-	-	71	-	-	-	-	-	-	-	-	71
30	teer company	388	26	51	127	56	44	15	27	13	17	6	10	736
31	Ncciraq	10	-	-	-	-	-	-	-	-	-	-	-	10
32	zheen	180	66	103	133	128	28	192	83	84	45	72	93	1207
33	hawler	30	18	46	39	49	-	41	74	38	30	45	34	444
34	zhyan	-	-	-	27	-	-	-	-	-	-	-	-	27
35	par	25	15	12	-	29	-	58	30	44	14	18	38	283
36	welfer	15	8	13	5	8	5	4	2	8	8	2	7	83
37	Istanbul	-	5	-	-	-	-	-	-	-	-	-	-	5
38	doctors without borders	150	-	-	60	-	-	-	-	-	-	-	-	210
39	rasul	-	-	-	7	-	-	-	-	-	-	22	36	65
40	Rahma	43	4	8	4	3	-	2	3	1	2	-	1,6	70
41	bahirka camp	30	27	-	-	-	-	-	-	-	-	-	-	57
42	western pharmacy	3	-	-	-	-	-	-	-	-	-	-	-	3

Appendix 3 continued

Medical hazardous waste generation from hospitals year 2017

43	medical university	-	10	-	-	-	-	-	-	-	-	-	-	10
44	shar	-	10	-	-	-	-	-	-	-	-	-	-	10
45	runahi centre	-	-	44	-	-	18	15	-	-	30	-	-	107
46	KHC company	-	-	-	-	999	-	-	-	-	-	-	-	999
47	mayser medical company	-	-	-	-	1	-	200	40	-	-	-	19	260
48	green hiber	-	-	-	-	-	20	-	-	-	-	-	-	20
49	child protection organization	-	-	-	-	-	250	-	-	-	-	-	-	250
50	umia company	-	-	-	-	-	-	180	-	-	-	-	-	180
51	ecology company	-	-	-	-	-	-	5	51	46	79	16	18	215
52	Triskan organization	-	-	-	-	-	-	56	-	-	-	-	-	56
53	Ayla centre	-	-	-	-	-	-	1	-	-	1	-	1	3
54	niga centre	-	-	-	-	-	-	-	2900	-	-	-	2,4	2900
55	American eye centre	-	-	-	-	-	-	-	-	20	3	-	2,4	23
56	DBB- blood bank	-	554	574	686	-	223	207	682	409	-	-	-	3335
57	tayrawa	10	10	18	41	-	-	72	81	40	122	98	32	524
58	nazdar bamarny	50	23	17	109	-	-	38	94	-	34	-	28	393
59	sarwaran	20	-	-	-	-	-	-	-	-	-	-	-	20
60	hawler teaching centre	50	-	-	54	-	12	-	72	-	47	-	-	235
61	DBB- blood bank	615	-	-	-	-	-	89	609	464	173	290	163,3	2240
62	zhyan	70	25	25	95	-	15	54	62	47	43	54	63	553
63	mala-fandy	-	-	-	-	-	-	-	-	-	-	-	-	0
64	raparin	350	330	174	100	-	-	-	80	10	-	-	50	1094
65	talasimia	60	122	65	135	-	40	70	87	95	73	67	64	878
66	childbirth	649	-	50	-	-	-	-	-	-	-	-	-	699
67	central lab.	110	170	142	75	-	50	332	180	210	113	86	143	1611
68	clinical centres	15	-	-	-	-	-	-	-	-	-	-	-	15
69	chest and surgical centre	-	17	15	-	-	-	-	-	-	-	-	-	32
70	kuran-ainkawa	-	-	-	-	-	-	-	-	-	-	-	-	0
71	emergency	20	-	35	-	-	-	-	-	-	-	-	-	55
72	psychological	-	-	-	-	-	-	162	-	-	-	-	33	195
73	rojhalat	-	-	120	-	-	-	-	14	-	25	-	-	159
74	Ministry of health	12	-	-	-	-	-	-	-	-	-	-	-	12
75	Mamun dabagh	15	20	15	20	-	10	-	30	11	-	11	50	182

Appendix 3 continued
Medical hazardous waste generation from hospitals year 2017

76	talasimia-ainkawa	-	-	25	-	-	-	-	-	-	-	-	-	25
77	pirzin	-	-	-	-	-	-	65	-	-	-	-	-	65
78	talasimia	-	-	-	-	-	-	155	-	-	-	-	-	155
79	khanzad	-	-	-	-	-	-	-	-	17	24	16		57
80	kasnazan	-	-	-	-	-	-	-	-	19	-	56	9	84
81	shahid Najeeb	-	-	-	-	-	-	-	-	-	-	22	-	22
82	shawes	-	-	-	-	-	-	-	-	-	-	18	-	18

Appendix 4
Medical hazardous waste generation from hospitals year 2018

No	Hospital name	Jan	Feb	Mar	Ap	May	June	July	Aug	Sep	Oct	Nov	Dec	Total (2018)
		Kg	Kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg/yr
1	westeye							12	6	8		7	8	41
2	sardam	37	12	13	15	21		48	34	45		11	36	271
3	rasul		13	71										83
4	sima	10	26		17	6	6			25		6	7	102
5	paky	32		60	169	248	101	183	50	148		159	135	1285
6	mother	40		12	16	15	13	13	4	19		19	19	170
7	eye teaching		6	4	13	6			1					30
8	Shami		4											4
9	Lala private			19	15	13	5	9	17	5		33	16	132
10	Shifa			5	9		3	2	3	5		5	6	38
11	rmsi											115		115
12	shar				20			9		10		15	22	76
13	media centre	20		35	58	52	9	43	47	29		30	85	408
14	welfer			5										5
15	alim university		72											72
16	knowledge university		10			38								48
17	zanko					6			4			7		17
18	double heat							6						6
19	Lebanon									12				12
20	balsam									11		11		22
21	dama organization									125				125
22	English village									20				20
23	step											23		23
24	barza company												39	39
25	Swedish												40	40
26	Azadi		22	20	17	20			18					97
27	shadi		49	45	22	26	16	25	9	9				201
28	heart centre	213	215	170	194	336	166	300	162	162				1918
29	Rizgary	6	35	26	35	35	5	33	244	18				437

Appendix 4 continued

Medical hazardous waste generation from hospitals year 2018

30	Layla Qasim	40	33	21	15	35	65	38	98	98				443
31	western emergency		346	19	13									378
32	blood centre	463	296	150	25	416	251	605	345	345				2896
33	nafih akreyi	10	28	15	15	16	8	40	43	43				218
34	Kurdistan	20	50	20	17	15								122
35	shahidan							10						10
36	hawler medical					4		1						5
37	industrial kidney centre								245	245				490
38	teer company				156	230,1	278	277	356	326	278	163	203	2037
39	IMC				20									20
40	zheen				136	85	82	174	107	165	106	141	106	1102
41	haawler				20	82	26	18	37	23	23		21	250
42	media centre				58			47	50			30		185
43	par				144	95	120	125	38	135	96	89	50	892
44	welfer				2	3	3	7	9	4	9	8	4	49
45	rasul				47	29	25	44	41	43	25	29	11	294
46	Rahma					2								2
47	American medical								8	18			23	49
48	runahi							50				50		100
49	mayser company					130						17		147
50	medical organization				25			25				42		92
51	Ayla centre									3				3
52	niga centre				2							4		6
53	American eye centre				4									4
54	US consulate general Erbil				28	28								56
55	medical clinic				3									3
56	hawler medical centre							3						3
57	daghr clinic									6				6
58	Cooperative medical organization										132			132
59	beauty centre										2	1	2	5
60	cente rsharqeye										2	2		4
61	DBB-Blood bank							222						222
62	tayrawa				75	24	20	38		56	51	36	3	303
63	nazdar bamarny				32	38	20	33	13	48	8	16	8	216
64	sarwaran									16	15			31
65	hawler medical						122	28		16	190			356
66	blood bank					470	500							970
67	zhyan				28	56	20			72	14	5	10	205

Appendix 4 continued

Medical hazardous waste generation from hospitals year 2018

68	raparin						200			160	220	200	180	960
69	talasimia				26	242	232	162		114	370	170	190	1506
70	hawler medical centre				11	450	400	473		265	474	250	260	2583
71	kuran-ainkawa										2	10		12
72	rojhalat emergency					72	153							225
73	Mamun dabagh					4	30	40		35	20		25	154
74	talasimia-ainkawa						81							81
75	pirzin									22			60	82
76	talasimia centre							162						162
77	khanzad				38					42				80
78	kaznazan						58							58
79	shahed dr. Habib				11	14	11			21	37	15	7	117
80	Mohammed bajalan									32		11	25	68
81	brayaty									20				20
82	ainkawa									46	40	10	10	106
83	health office												60	60

Appendix 5

Medical hazardous waste generation from hospitals year 2019

No	Hospital name	Jan	Feb	Mar	Ap	May	June	July	Aug	Sep	Oct	Nov	Dec	Total (2019)
		Kg	Kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg/yr
1	westeye	20	7	8	8	20	7	7	8	7	2	5		99
2	sardam	38	12	61	11	61	18	26	19	39	17	18	53	373
3	sima	3						4		7	6			20
4	paky	102	95	150	199	68	88	20	17	62	46		30	877
5	mother			19	19	38	9	19	19		19	19	19	180
6	eye	2							2			2	9	15
7	soma			30						25				55
8	Lala	36	13	34	28	12	4		15	5	11	16	23	197
9	Shifa	3	6	5	7	7		7	5	6		5	7	58
10	RMSI		29			5								34
11	shar		18		13		16	17	10		25	10		109
12	media centre	54	78	131	63	80	44	60	49	91	47	61	32	790
13	knowledge university									10				10
14	zanko		16										22	38
15	balsam	55						25			27			107
16	step				30									30
17	new vision eye				2	11								13
18	honia clinic						12							12
19	Shet bn Clinic							15						15
20	IMC							10	44					54

Appendix 5 continued
Medical hazardous waste generation from hospitals year 2019

21	IOM									3				3
22	bouble hair										5			5
23	Azadi	15	20	15	60	45	59	32	32	25	18	51		372
24	shady	11	30	20	55	47	54	27	27				26	297
25	heart centre	134	110	130	205	846	1159	1698		110	240	5460	336	10428
26	Rizgary	80	114	280	220	2700	2967	550	73	73	2210	2700	35	12002
27	Layla Qasim	65	50	50	70	35	62	86	35	20	16	27	60	576
28	blood centre	415	500	60045	680	950	950	1087						64627
29	nafih akreyi	43	30	45	60	80	73	35	35	10	18	428	20	877
30	kurdistan												15	15
31	hawler teaching medical centre												1500	1500
32	industrial kidney centre	202		302	700	1500	2580	2850	20000	2400	2550	2847	2750	38681
33	teer company	152	43											195
34	zheen	151	153		203			115	123	149	69		127	1090
35	Hawler	163	17		20					28			487	715
36	Swedish private												57	57
37	par	66	72		70			133	107	214	138		140	940
38	welfer	6	8		5			133	73	51	4		41	320
39	CMC		24		24			45			47		23	163
40	Rasul	37						16		62	46		35	196
41	Rahma							1						1
42	American university								12					12
43	shar		18											18
44	runahi centre		31										40	71
45	mayser												30	30
46	doctors without borders										23			23
47	Ayle				3			2						5
48	niga centre												3	3
49	beauty centre	4	13		7			3			4		1	31
50	Sharq for eye				2					1				3
51	LST		55											55
52	new rasul		29		28				17				22	96
53	IMC		29											29
54	shar		580											580
55	balsam				30									30
56	hawler private							23	28		14		377	442

Appendix 5 continued
Medical hazardous waste generation from hospitals year 2019

57	imagine centre							2						2
58	CMC								75		47		23	145
59	hawler hospital for fertility Genetics								4	4				8
60	omer daghir clinic										5			5
61	Marvin beauty										17			17
62	blood bank centre							795	787					1582
63	tayrawa	7	8					13	9	72	382		4	495
64	nazdar bamarny	5												5
65	hawler teaching medical centre		366		250			200	600	1340	1320	910	1957	6943
66	blood bank centre	637	529								1035		1110	3311
67	zhyan	3	4											7
68	raparin		100					132		300		200	90	822
69	talasimia		135		25			225	100	310	100	950	150	1995
70	childbirth	6			25									31
71	hawler medical lab	130	131		60			430	200	340	320	320	260	2191
72	kuran-ainkawa		11					7						18
73	emergency										25			25
74	rojhala		20								295	95	375	785
75	Mamun dabagh	300	35		40			40	8	40		40	50	553
76	pirzin								45			32		77
77	talasimia	135						225						360
78	shahid dr Habib	10	11		13			10	10	21	15	4	3700	3794
79	shawes												4	4
80	Mohammed bajalan							20						20
81	ainkawa	12	53		5			7		48	18	312	215	670
82	chest and surgical breast	65												65
83	darashakran							47				557		604
84	kawrgosk							150				115		265
85	shadi									20				20
86	blood bank centre									1658		775	1110	3543
87	Layla Qasim									80				80
88	Rizgary									45			76	121

Appendix 5 continued

Medical hazardous waste generation from hospitals year 2019

89	kidney centre (west)									400				400
90	shadi									20				20
91	hawler medical centre											80		80
92	Fryakawtni nawand												76	76

Appendix 6

Medical hazardous waste generation from hospitals year 2020

No.	Hospital names	Jan	Feb	Mar	Ap	May	June	July	Aug	Sep	Oct	Nov	Dec	Total (2020)
		Kg	Kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg/yr
1	media	86	20		11	155	84	86						356
2	sardam	65	15		79	47	39	65						245
3	Shifa	7	7											14
4	westeye	11	6											17
5	mother	19	29			20	20							88
6	paky	41				24								65
7	Rmsi	40												40
8	Shar	19												19
9	Lala	16	12	15										33
10	balsam	27	100	70										134
11	awamedica	388												388
12	eye		11											11
13	IOM		29											29
14	sima		5											5
15	double hair		5											5
16	RWA		2											2
17	shayda beuty		3			10								13
18	shar		46				20							66
19	IMC						15							15
20	Layla	35												35
21	heart centre	4500												4500
22	nafih Akreyi	55												55
23	shadi	15												15
24	Azadi	45												45
25	industrial kidney	6000												6000
26	hawler private	484	655											1139
27	zheen	154	173											327
28	Santa maria	16												16
29	new rasul	48	30											78
30	CMC	55	27											82
31	mayser company	13												13
32	local medical	4												4
33	beauty centre	5												5
34	welfer	27	20											47
35	par	123	81											204
36	sharq		1											1

Appendix 6 continued
Medical hazardous waste generation from hospitals year 2020

37	LST		46											46
38	blood bank	640	390											1030
39	general medical centre	80	240											320
40	rojhalat centre	310	15											325
41	talasimia	235	70											305
42	kawrgosk	75												75
43	ainkawa	10	2											12
44	shahid dr Habib	5	3											7
45	hawler medical		2415											2415
46	shaqlawa		74											74
47	raparin		50											50
48	sarwaran		42											42
49	pirzin					11								11
50	par/corona									417				417
51	tayrawa									155				155
52	brayati									60				60
53	shahid Salih									4				4

Upravljanje bolničkim otpadom: tretman, skladištenje i odlaganje

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I Z V O D

Brzi porast broja stanovnika, industralizacija i rast potražnje za sirovinama za industrijsku i medicinsku proizvodnju su doveli do stvaranja velike količine opasnog otpada. Opasan otpad se identifikuje prema svojoj toksičnosti, zapaljivosti i radioktivnosti. Odlaganje opasnog otpada u prirodnu sredinu ima značajan uticaj na zdravlje i sva živa bića u životnoj sredini. Danas veliki broj bolnica i industrijskih pogona stvara velike količine opasnog otpada. Cilj ovog rada je procena sistema upravljanja opasnim bolničkim otpadom u Erbilu. Pored toga, fokus je na upravljanju opasnim bolničkim otpadom i karakterizaciji i stanju u Erbilu. Stopa proizvodnje opasnog otpada iz bolnica u Erbilu je prikupljena za 12 meseci, u periodu od 2015. do 2020. godine. Rezultati su pokazali da je najveća količina ovog otpada nastala tokom 2019. godine. Štaviše, potrebno je povećati broj centara za spaljivanje otpada na licu mesta kao bi se smanjili troškovi skladištenja i transporta.

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Geopolymer Concrete: Properties, Durability and Applications-Review

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ABSTRACT

Concrete is one of the most reliable, durable, and desired construction materials. It became the second most used material after water in the world. Many studies and investigations reported that the amount of CO_2 released into the atmosphere is nearly 1 ton in the production of 1 ton of cement, which contributes to 5-7 % of total CO_2 emissions worldwide. Geopolymer concrete (GPC) is a new development in the world of concrete, which does not need to use cement. The most used materials in geopolymer are by-products such as fly ash, ground granulated blast furnace slag, silica fume, etc. Industrial waste materials are a great problem for human health, environment, and scarcity of land, therefore, reusing them in GPC manufacturing can be seen as a great advantage. Fortunately, most of the recent research concludes that most by-products exhibit similar or better durability, mechanical and physical properties when compared to ordinary concrete. Therefore, GPC became a good sustainable engineering material with many advantages over conventional concrete, such as high early strength, excellent resistance to chemical attacks and steel reinforcement corrosion, elimination of water curing, low cost, etc. This paper reviews the process of geopolymer concrete, constituents, types, properties, durability, and particular applications.

1. Introduction

Establishing factories and industries is the main factor for the development of any country, and it has become a huge source of incomes. The industrial sector currently increased worldwide which is the great sources of CO_2 emissions, which are harmful for the environment in various ways and the results are global warming, greenhouse gases, etc. To conserve water from contamination by any disposal and protect lands, the industries should reduce waste by recycling or reusing and reducing CO_2 by capturing and storage. Related to civil engineering, construction has been one of the rapidly growing fields.

A lot of effort is put in reducing the use of cement, one of the changes is partial replacement of cement by other cementitious materials such as by-product materials e.g., fly ash, slag. These types of cements are called blended cements, because they are mixed with ordinary cement. Another new technology is the complete replacement of cement by a natural or waste materials (Law et al., 2015), which is rich in silica and alumina, it can be applied as a binder instead of cement in concrete.

This new innovation is called Geopolymer, firstly formed by French chemist Joseph Davidovits in 1978 (Davidovits, 1994). Geopolymer concrete (GPC) is a good alternative for conventional concrete, it provides excellent mechanical properties and durability such as strong resistance to acids, thermal and freezing-thawing attacks.

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2. GPC (Geopolymer concrete)

Geopolymer is a new development class of concrete. It is a new idea to avoid using cement and completely replace it, thus become an eco-friendly material. This system is based on an inorganic Aluminosilicate binder, that is any source material that is rich in alumina (Al) and silica (Si) can be used, especially by-products such as; fly ash, slag, natural rocks, etc. The source material is mixed with an alkaline activator (usually KOH or NaOH) to liberate Al and Si atoms, with an additional source of silica (Na_2SiO_3 commonly used) to activate the atoms. In the chemical reaction of GPC water is not involved, it is expelled during curing, which resultes in no water content. Therefore, the hydration reaction that occurs in ordinary concrete is released and the hydration production (Calcium-Silicate-Hydrate, Calcium Hydrate) is also released. These results show great advantages in terms of the mechanical properties (Sathia et al., 2008), alkali-aggregate reaction, lower sorptivity (Shaikh, 2014) and other chemical attacks. Geopolymerization process involves a chemical reaction under strongly alkaline conditions, the product is in the form of a strong gel with an amorphous (Non-Crystalline) microstructure based on Al-Si system. It can exhibit the ideal properties e.g. hardness, longevity and chemical stability. The important fact is that high-alkali binder does not generate an alkali-aggregate reaction. Its structure consists of three-dimensional links of SiO_4 (Silate) and AlO_4 (Tetrahedra) with shared oxygen atoms. Figure 1 shows the formation process of geopolymer (Davidovits, 1994).

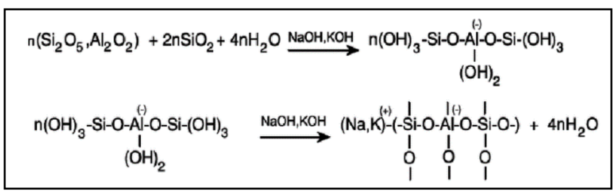

Figure 1. Schematic formation of geopolymer (Davidovits, 1994)

3. Constitution of GPC

The main ingredients of the GPC are source material and alkaline solution, also aggregate (both coarse and fine), water and admixture.
GPC = Aluminosilicate by-products (precursors) + Alkaline Activator + Aggregate + Water + Admixture.

3.1. Source (base) material

The base material used is a dry and very fine powder, its fineness is almost higher than cement, which helps in better reaction and bonding. Pozzolanic compound or other Aluminosilicate material can be used in the production of a geopolymer that is used instead of cement and acts as a binder in concrete. Natural materials such as kaolinite, clay and other alternatives especially by-product materials e.g. Fly ash (Bakri et al., 2012; Hariz et al., 2017), Ground granulated blast-furnace slag (GGBS), silica fume, rice-husk ash (Bakri et al., 2012), red-mud (Burduhos Nergis et al., 2018), metakaolin, etc. can be used. Various industry by-products and hazardous wastes can be used to manufacture geopolymers (Hajimohammadi and van Deventer, 2017; Bagheri et al., 2018; Hu et al., 2018).

In order to promote more environmental-friendly production using waste materials more than naturals have been suggested to minimize CO_2 emissions, using less energy and conserving more land. Also using locally available source materials helps in minimizing the total cost.

3.2. Alkaline activator

The liquid solution is another main ingredient of geopolymer. Alkali activation is a process of mixing Aluminosilicate material with an alkaline activator, it produces a paste that sets and hardens. This process is done with the availability of some amount of water. Bakri et al. (2012) stated that, the most common used alkaline liquids are mixture of sodium hydroxide with sodium silicate (Na_2SiO_3) or potassium hydroxide (KOH) with potassium silicate (K_2SiO_3). Selecting the types of activators mainly depend upon availability and reactivity. NaOH is cheaper and more reactive compared to KOH (Sathia et al., 2008).

3.3. Aggregates

Aggregates are the other main ingredients of GPC. In normal concrete, coarse aggregate and fine aggregate are usually used by 65 % and 35 %, which occupy almost 70 % of concrete volume (Chowdhury et al., 2021). The ratio of aggregates is also same for GPC, while the studies by Kashani et al. (2019) reported that the use of fine aggregates to coarse aggregates at a ratio of 0.53:0.47 to achieve self-compactness without decreasing required strength. Locally available aggregates are recommended to use in geopolymer in order to become more economical. Table 1 shows the type and some physical properties of both coarse and fine aggregates used in GPC by different researchers.

3.4. Admixtures

To maintain the workability of the GPC, it is better to use admixtures other than using extra water. Some commonly used superplasticizers are Sulfonated naphthalene formaldehyde and Sulfonated melamine formaldehyde (Chowdhury et al., 2021). High-Range-Water-Reducer admixtures such as naphthalene-based superplasticizer (Sathia et al., 2008; Joseph and Mathew, 2012; Singh et al., 2015), MasterGlenium ACE_450

Table 1
Types and physical properties of aggregates

Author	Aggregate	Type	Nominal size (mm)	Specific gravity
(Mesgari et al., 2020)	Coarse	Recycled GPC	12	2.85
	Fine	Sydney sand	-	2.6
(Joseph and Mathew, 2012)	Coarse	Crushed granite rock	20	2.72
	Fine	Natural river sand	4.5	2.64
(Gupta et al., 2021)	Coarse	-	20	2.81
	Fine	-	4.75	2.66
(Jamkar et al., 2013)	Coarse	Crushed basalt	12.5	2.639
	Fine	Natural river sand	4.75	2.563
(Mucsi et al., 2014)	Coarse	Metallurgical converter slag	22.4	-
	Fine	Andesite	4	-
(Jawahar and Mounika, 2016)	Coarse	Crushed granite stones	10, 20	-
	Fine	Natural river sand	-	-

(Safari et al., 2020) were used to increase relative slump without any decrease in compressive strength. Admixtures such as sucrose ($C_{12}H_{22}O_{11}$) is used as retarder since it is absorbed by Al, Ca and Fe ions to form insoluble metal complexes. Also citric acid ($C_6H_8O_7$) acts as accelerator reducing the setting time (Kusbiantoro et al., 2013; Singh et al., 2015).

Admixtures in the ratio of 1-2 % (Rattanasak et al., 2011), 1-2.5 % (El-hassan and Ismail, 2017), and 2 % (Joseph and Mathew, 2012; Safari et al., 2020) were added by mass of the source material.

4. Production of GPC

Similar to the hydration reaction of ordinary Portland cement (OPC), geopolymerization is also an exothermic reaction, it releases a large amount of heat during mixing. The process can be divided into three stages:

1. Preparing the alkaline solution by mixing NaOH and Na_2SiO_3 or KOH and K_2SiO_3 with availability of some amount of water. To completely dissolve the chemical substances in each other this preparation should be at least 24 hours prior (Bakri et al., 2012; Safari et al., 2020).
2. Mixing dry materials such as source material and aggregates then mixing with the prepared chemical solution and adding the admixtures to maintain workability, then moulding. In this state (fresh state) the concrete can easily handle up to 120 minutes without any sign of setting and without any degradation in its compressive strength.
3. Leaving the samples at room temperature for 24 hours. Then solidification through curing the samples after de-moulding them either at ambient temperature or by heating using oven. Most of the researches are agree on oven curing in 60º C to 100º C for 24 to 96 hours (Kumar et al., 2015). In this stage the water is totally eliminated and the material shows its final form.

The production process of GPC is summarized in the Figure 2 (Hassan et al., 2019; Masoule et al., 2022).

5. Types of GPC

5.1. Fly ash-based geopolymer

Fly ash is a pozzolanic waste material, pozzolans are siliceous or siliceous and aluminous materials. Generally, fly ash is generated in the coal-fired power plant. Its particles are glassy and spherical, based on its sources and composition can be classified into two classes; class F of fly ash which is produced from burning of bituminous or anthracite coal also contains less than 7 % lime (CaO), the second type is class C which is normally produced from burning of sub-bituminous or lignite coal, contains more than 20 % lime. Fly ash is available in huge quantities worldwide. Class F of fly ash has been investigated as a suitable material for geopolymer because of its pertinent silica and alumina composition, less water demand, and wide availability (Nath and Sarker, 2014; Jawahar and Mounika, 2016). Fly ash has strong and glassy silica-alumina chains, these chains are broken by alkali activators. Using fly ash in geopolymer is a good choice due to its ability to maintain good workability, durability and compressive strength. The main chemical compositions of fly ash classes are tabulated in Tables 2 and 3, respectively.

5.2. Slag-based geopolymer

Slag is a waste material that produced during the melting of iron ore (Burduhos Nergis et al., 2018). Slag has different types such as Granulated Corex slag (GCS), steel slag, blast furnace slag (BFS), GGBS, etc. It can be used in manufacturing different types of materials also used to create binders in different types of concrete and mortars with a very good mechanical property by geopolymerization. Compared to fly ash, slag is more preferable to use in producing geopolymer, because its behaviour is more similar to OPC and it has the same main chemical composition like OPC but in different proportions while fly ash has slowly pozzolanic reaction. The main chemical compositions of GGBS, GCS, and BFS are shown in the Table 4.

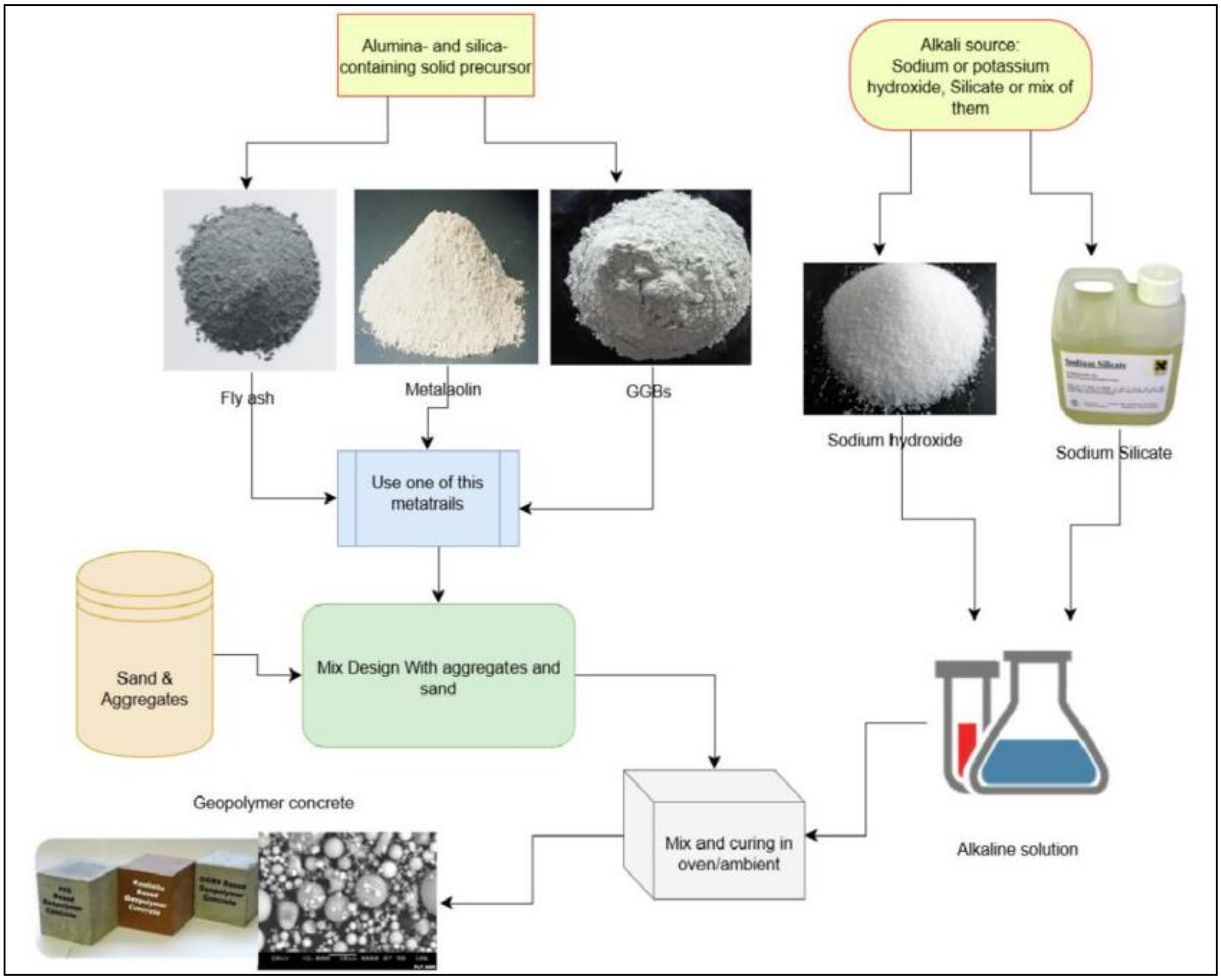

Figure 2. Production process of GPC (Hassan et al., 2019; Masoule et al., 2022)

Table 2
Chemical composition of fly ash

Fly ash	Author	Chemical Composition %					
		Al_2O_3	SiO_2	CaO	Fe_2O_3	MgO	SO_3
Class F	(Sathia et al., 2008)	30.08	61.16	1.75	4.62	0.18	0.19
	(Huseien et al., 2016)	28.80	57.20	5.16	3.67	1.48	0.1
Class C	(Muthadhi et al., 2016)	31.23	32.62	17.12	8.48	3.49	0
	(Wardhono et al., 2017)	17.89	4.75	12.65	59.11	0	0.86

Table 3
Chemical composition of fly ash classes

Fly ash (Burduhos Nergis et al., 2018)	Chemical Composition
For class F	$Al_2O_3 + SiO_2 + Fe_2O_3 \geq 70$ %
For class C	$Al_2O_3 + SiO_2 + Fe_2O_3 \geq 50$ %

Table 4
Main chemical composition of GGBS, GCS, and BFS

Material	Author	Chemical Composition %					
		Al_2O_3	SiO_2	CaO	Fe_2O_3	MgO	SO_3
GGBS	(Huseien et al., 2016)	10.9	30.80	51.80	0.64	4.57	0.06
	(Jawahar and Mounika, 2016)	16.24	30.61	34.48	0.584	6.79	1.85
GCS	(Mehta and Siddique, 2016)	18.36	32.51	33.31	1.49	11.08	-
BFS	(Mehta and Siddique, 2016)	11.50	33.80	38.30	0.60	9.0	-

5.3. Red -mud -based geopolymer

Red mud is another source material that can be used in GPC. It is generated in huge amount from aluminium production plant, its pH is about 10.5-12.5 (Rai et al., 2012). Burduhos Nergis et al. (2018) stated that 2 ton of red mud are deposited for every ton of aluminium. Red mud is rich in silica and alumina, thus it can be used to create geopolymer and its ions dissolved in NaOH at 175 ºC, resulted in produce of $Al_2(OH)_2$ (Burduhos Nergis et al., 2018). It has excellent quality with low cost and CO_2 emissions but the main problem of red mud is that it cannot be reused, hence it becomes a huge problem for environment in future (Rai et al., 2012). Table 5 shows the main chemical composition of Red-mud.

5.4. Metakaolinite based-geopolymer

Metakaolin is a type of refined kaolin clay calcined at temperature between 650 °C and 750 °C (Burduhos Nergis et al., 2018). It is an aluminosilicate material which can be used in manufacturing of geopolymer concrete (Parathi et al., 2021). Its ions can be dissolved in NaOH at 100-150 ºC (Rovnaník, 2010). It can emit 80-90 % less CO_2 than OPC. Metakaolin-based GPC has higher strength and durability compared to OPC concrete (Guo et al., 2020). Granizo et al. (2007) stated that the chemical constituents of metakaolin directly influence the mechanical properties of GPC. The main chemical composition of three types of kaolin (Granizo et al., 2007; Heah et al., 2011) and metakaolin (Rovnaník, 2010; Mehta and Siddique, 2016; Zain et al., 2017) are shown in the Table 6.

The difference between cementitious materials (silica fume, natural pozzolans, metakaolin, fly ash, slag, limestone and OPC) based on chemical compositions (Al_2O_3, CaO and SiO_2) are shown in a ternary diagram in the Figure 3.

Table 5
Main chemical composition of red-mud

Material	Author	Chemical Composition %					
		Al_2O_3	SiO_2	CaO	Fe_2O_3	MgO	TiO_2
Red-mud	(He et al., 2013)	14	1.20	2.50	30.9	-	4.5
	(Kaya and Soyer-Uzun, 2016)	14.02	11.67	1.10	37.1	0.23	5.78
	(Mehta and Siddique, 2016)	0.45	89.34	0.76	0.4	0.49	-

Table 6
Main chemical composition of kaolin and metakaolin

Author	Material	Chemical composition %				
		Al_2O_3	Si_2O_3	CaO	Fe_2O_3	MgO
(Granizo et al., 2007)	Kaolin 1	36.3	49.8	0	0.6	0.2
	Kaolin 2	36	47	0.8	0.5	0
(Heah et al., 2011)	Kaolin	35	52	<0.05	1.0	0.70
(Rovnaník, 2010)	Metakaolin	40.94	55.01	0.14	0.55	0.34
(Mehta and Siddique, 2016)	Metakaolin	40.48	48.31	0.04	2.62	0.36
(Zain et al., 2017)	Metakaolin	37.20	55.90	0.11	1.7	0.24

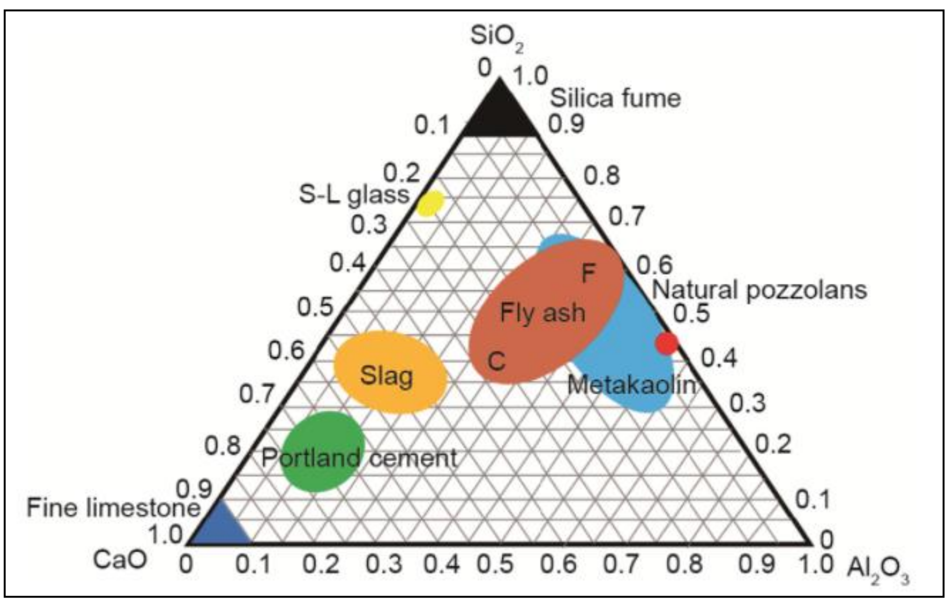

Figure 3. Al_2O_3 – CaO – SiO_2 ternary diagram for cementitious materials (Wang et al., 2020)

6. Mechanical properties

The behaviour and properties of any concrete should be studied from preparing the ingredients to its full life-cycle in order to learn how to deal with the possible issues. According to previous studies when compared to conventional concrete, GPC has more excellent properties such as, high early strength and durability. Sathia et al. (2008) reported that the time of hardening in GPC is very short, 90 % of its strength is obtained within 7 days and after that there are no more variation in compressive strength. There are a lot of factors that have a great influence on the compressive strength of the GPC. The main effective factors are: concentration of the alkaline activator, curing time and temperature. Also, Burduhos Nergis et al. (2018) added other factors like; molar ratio of SiO_2 to Al_2O_3, Na_2O to SiO_2, H_2O to Na_2O, type and quantity of the admixture, particle dimensions, calcium quantity and fineness of the source material and aggregates.

6.1. Alkaline solution

The main factors affected the mechanical properties of GPC regarding the alkali solution are; Na_2SiO_3 to NaOH ratio, ratio of alkali to binder (Raijiwala and Patil, 2011). Bhikshma (2012) worked on fly ash-based geopolymer, used different alkaline to binder ratio. The experimental results showed that all compressive, tensile and flexural strength increased with increasing alkaline to fly ash ratio, in Figure 4.

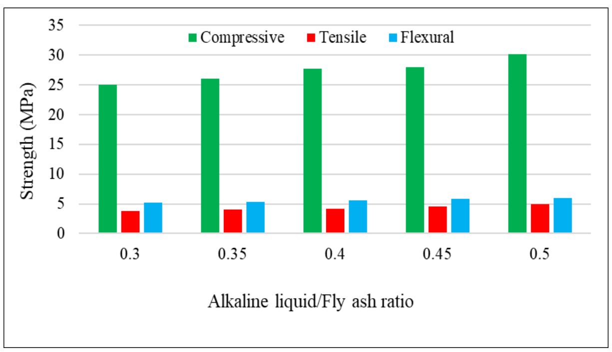

Figure 4. Effect of Alkaline liquid/fly ash ratio on compressive strength (Bhikshma, 2012)

The explained factors can increase the compressive strength in a limited range, beyond that range it will have adverse effect. In addition, compressive strength decreases with increasing H_2O to Na_2O ratio. Because the water evaporates during curing and it leads to increased porosity, decreased density and poor compressive strength. Moreover, Huseien et al. (2016) stated that increasing the ratio of water to geopolymer, resulted in decreasing compressive strength. Wu et al. (2019) reported that increasing of SiO_2 to Al_2O_3 ratio resulted in decreasing of compressive strength.

6.2. Liquid concentration

Concentration (in terms of molarity M) of the alkaline activator is one of the factors which influence the mechanical properties of GPC (Hardjito et al., 2004; Raijiwala and Patil, 2011). Compressive strength increases with increasing concentration of the liquid, alkaline to binder ratio and Na_2SiO_3 to NaOH ratio. Because higher concentration means higher -OH ions thus rapid disintegration and higher solubility of silica-alumina chains of source material in the solution. Hence contribute the production with larger number of active groups resulted in higher early compressive strength (Sathia et al., 2008; Jawahar and Mounika, 2016).

Practically, Burduhos Nergis et al. (2018) used concentration 4, 8, and 12 M, Raijiwala and Patil (2011) applied 8, 10, 12, 14, 16, and 25 M and Huseien et al. (2016) used 2, 4, 6, 8, 10, 12, 14 and 16 M, they tested the samples for 28 days. Their results showed that the compressive strength of GPC increases with increasing liquid concentration in a specific range, in Figure 5.

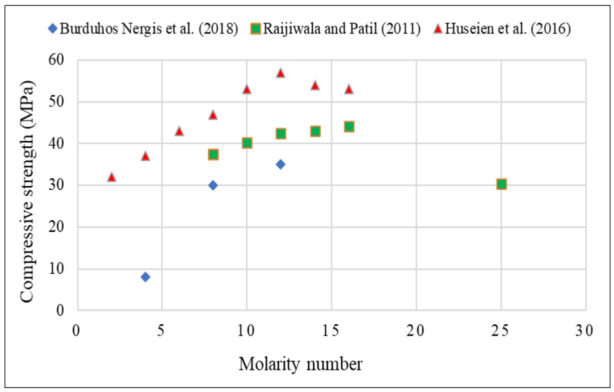

Figure 5. Effect of NaOH concentration on compressive strength

Through reviewing the previous studies and investigations on geopolymer, there should be an optimum level for the liquid concentration and SiO_2 to Al_2O_3 ratio and H_2O to Na_2O ratio. Most of the researchers found the optimum level in 12 Molarity of the concentration and (2.5 to 4) for SiO_2 to Al_2O_3 ratio of precursor materials (Bakri et al., 2012; Safari et al., 2020).

6.3. Curing time and temperature

There is a difference between curing in OPC concrete and GPC; in OPC concrete water is used to cure the samples but in geopolymer system the samples can be cured in room temperature (ambient curing) or by heat (steam or dry curing) to facilitate the geo-polymerization rate. The temperature during curing depends upon source material and activating solution. Increasing curing temperature results in accelerated geopolymerization process, decreased setting period and contribution to higher compressive strength in short time (Shaikh, 2014;

Burduhos Nergis et al., 2018). Vijai et al. (2010) studied effect of different curing times and temperatures and used ambient and hot curing for 7 and 28 days, respectively. The results showed that the compressive strength increased with increasing curing temperature and curing period. The results are shown in Figure 6.

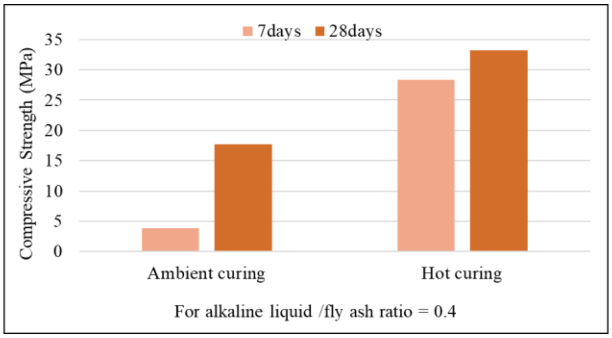

Figure 6. Effect of curing time and temperature on compressive strength (Vijai et al., 2010)

Zhang et al. (2016) showed that compressive and flexural strength increased with increasing curing temperature 25 ºC to 100 ºC, but beyond 100 ºC they were decreased, in Figure 7.

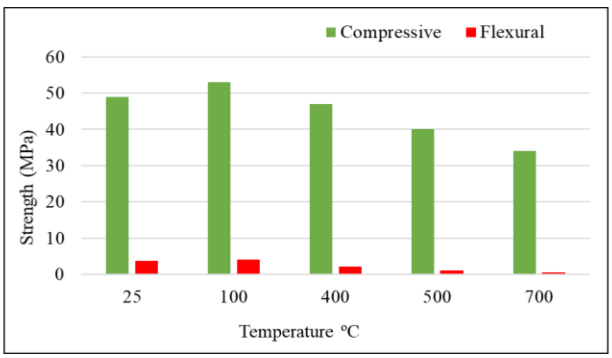

Figure 7. Effect of curing temperature on compressive and flexural strength (Zhang et al., 2016)

Raijiwala and Patil (2011) worked on geopolymer, fixed 16 molarity concentration for all samples then tested in different curing time. The compressive strength, split tensile, and flexural strength increased with time of curing, Figure 8.

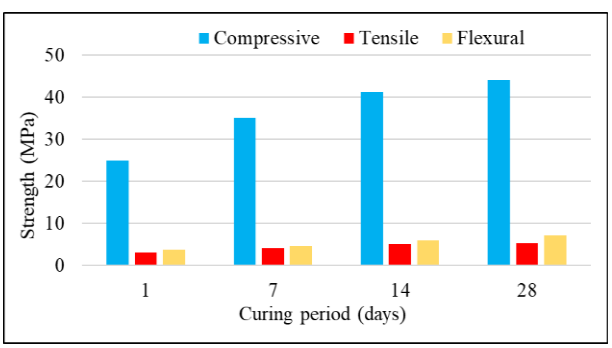

Figure 8. Effect of curing temperature on compressive, tensile and flexural strength (Raijiwala and Patil, 2011)

6.4. Fineness

The fineness of the source material was also studied by some researchers. Chowdhury et al. (2021) used fly ash in geopolymer concrete with specific surface area of 250-500 m^2/kg and (542, 430, 367, 327, 265) m^2/kg were used by Jamkar et al. (2013). They concluded that, the fineness of the source material is directly related to the density of the geopolymer material. The finer particle size of source material, the larger the specific surface area and the higher the reactivity (Gupta et al., 2017; Al-Mashhadani et al., 2018; Assi et al., 2018). The fineness of the aggregates is also significant in order to evaluate the performance of geopolymer materials. Table 7 shows the type and fineness modulus of fine aggregate used in different studies.

Table 7
Types and fineness modulus of fine aggregate

Author	Type of fine aggregate	Fineness Modulus
(Nuaklong et al., 2016)	Natural river sand	2.6
(Joseph and Mathew, 2012)	Natural river sand	2.36
(Jamkar et al., 2013)	Natural river sand	3.16
(Gupta et al., 2021)	-	2.83
(Aly et al., 2019)	Natural sand	2.25

7. Durability

The durability of concrete is an important issue that should be considered in the performance of the structure throughout its lifecycle. The durability of concrete mainly depends upon its permeability characteristics. When concrete is impermeable, it means that it can resist penetration by any aggressive ions, thus reduce damaging of the concrete, maintenance cost and extend its life-cycle expectancy. Most of the researches reported the excellent durability in geopolymer system due to less steel corrosion, creep, drying shrinkage, acid attacks, chloride attack, water sorptivity (Shaikh, 2014), porosity, and high temperature resistance up to 600 ºC, heat insulation, strong interfacial bonding and higher sustainability. The mass loss in geopolymer paste due to exposure of H_2SO_4 is about 3 % which is less than ordinary Portland cement (Sathia et al., 2008). All the parameters which affect the properties and performance of the GPC also affect the durability. Higher water absorption occurs with increasing NaOH molarity and reducing fine aggregate content while by curing at lower temperature (ambient), the water absorption decrease when compared to curing at elevated temperature (Huseien et al., 2016). Furthermore, using more Na_2SiO_3 leads to lower water absorption and better corrosion resistance. However, using higher alkaline solution to binder ratio will have negative effect and increase water absorption.

Sathia et al. (2008) stated that increasing H_2O to Na_2O ratio decreases the compressive strength due to increasing porosity.

Huseien et al. (2016) studied the effect of sodium hydroxide molarity on water absorption in geopolymer mortar. The test results after 24 hours showed that water absorption decreases with increasing NaOH concentration, Figure 9.

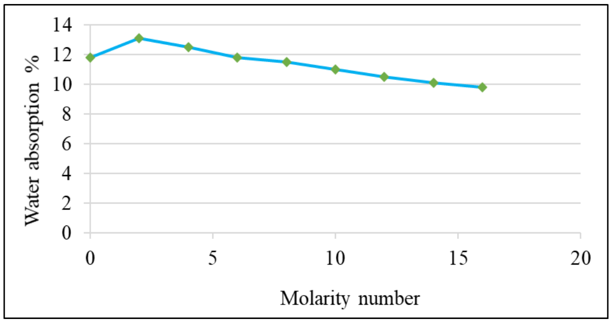

Figure 9. Relation between molarity and water absorption (Huseien et al., 2016)

Raijiwala and Patil (2011) studied the effect of NaOH molarity and curing time on durability of GPC, used 8, 10, 12, 14, 16, and 25 M and tested in 1, 7, 14, and 28 days for weight loss amount. The results showed that the weight loss decreased with increasing molarity and curing period until 16 M but after that it was increased, Figure 10.

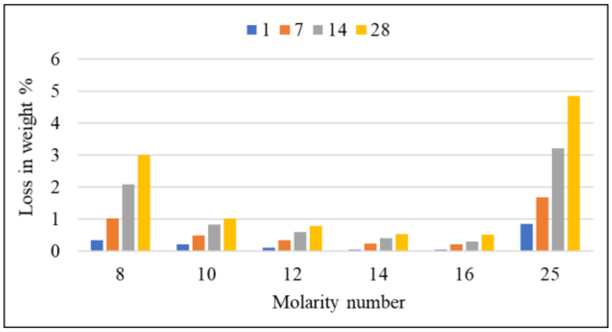

Figure 10. Effect of molarity and curing time on weight loss in compressive strength (Raijiwala and Patil, 2011)

Davidovits (2013) showed that the expansion due to alkali-aggregate reaction in OPC is much higher than GPC, it is shown in the Figure 11.

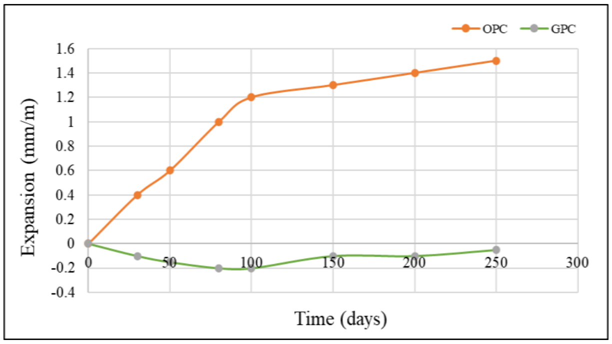

Figure 11. Expansion due to alkali-aggregate reaction (Davidovits, 2013)

Compared to OPC-based concretes, fly ash-based geopolymer has less tendency for shrinkage and cracking and has much less effect of fire when exposed to fire. Sarker et al. (2014) reported that GPC has more resistance to loss compressive strength at high temperature than OPC concrete, when both of them were exposed to fire from 23 ºC to 1000 ºC. The variation is shown below in Figure 12.

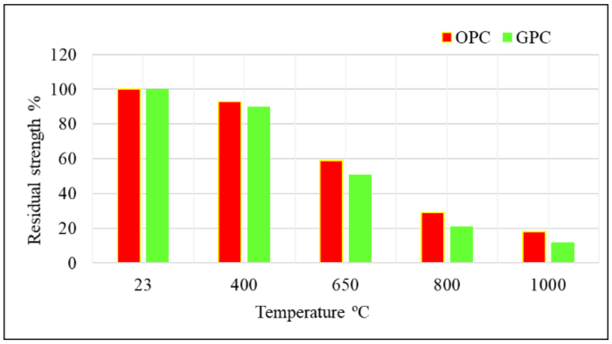

Figure 12. Residual of compressive strength after exposure to fire (Sarker et al., 2014)

Lavanya and Jegan (2015) studied durability of OPC concrete and GPC, they evaluate the reduction in compressive strength and density when exposed to magnesium sulphate and sulfuric acids. The reductions were less in GPC compared to OPC concrete, Table 8.

Table 8
Reduction in compressive strength and density for plain and geopolymer concrete (Lavanya and Jegan, 2015)

Type of exposure	Type of concrete	Loss in compressive strength %	Decrease in density %
Sulfuric acid	OPC	18 - 28	5 - 7
	GPC	12 - 20	2.5 - 4
Magnesium sulphate	OPC	5 - 25	4 - 6
	GPC	5 - 12	2 - 3

Hardjito et al. (2004) investigated the durability of geopolymer concrete by evaluating its resistance to sulphate attack. They performed a series of tests, the test samples were soaked in 5 % sodium sulphate (Na_2SO_4) solution for a period of time. After 12 weeks from immersion, the samples were tested. The results showed no significant changes in the compressive strength, its mass and in the length of the specimens.

Astutiningsih et al. (2010) studied the effect of seawater on compressive strength of fly ash-based geopolymer concrete. The geopolymer concrete samples were cured at room temperature for 24 hours, then removed from their moulds and left at room temperature for 14 days, while the normal concrete samples were cured in water for 28 days to maintain complete hydration. After curing the samples, all samples were immersed for 7, 28, 56, and 90 days in ASTM seawater. The compressive strength of both kinds of concretes were measured and compared. See figure 13 and 14.

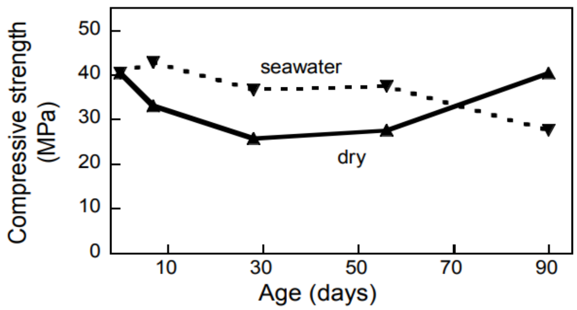

Figure 13. Effect of seawater immersion on compressive strength of geopolymer (Astutiningsih et al., 2010)

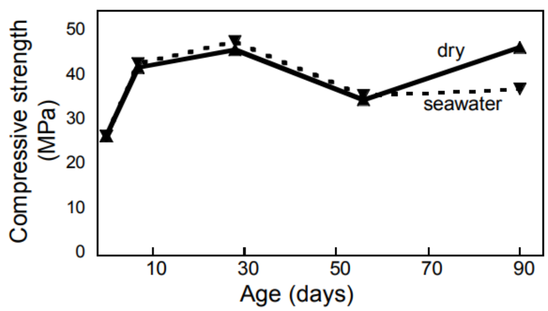

Figure 14. Effect of seawater immersion on compressive strength of cement-based concrete (Astutiningsih et al., 2010)

Other studies have been performed to evaluate the short and long-term durability of geopolymer composites in different ways. For example, Bakharev (2005) studied resistance of geopolymer materials to acid attacks, acetic and sulfuric acids. Thokchom et al. (2009) and Albitar et al. (2017) examined the effect of water absorption, sorptivity, porosity on durability of geopolymers. (Farhana et al., 2015) studied the relationship between porosity and water absorption in geopolymer concrete. Law et al. (2015) investigated on water sorptivity and chloride permeability of geopolymer concrete. Pasupathy et al. (2018) observed on fly ash-based geopolymer under atmospheric condition for 8 years. Aygörmez et al. (2020) worked on durability of geopolymer composite at one year, and Gupta et al. (2021) studied effect of varying admixture dosage on durability geopolymer concrete composite.

8. Applications

Geopolymer cement can be used in construction, transportation infrastructure and offshore applications. GPC can be used in precast industries due to high early strength and less breakage during transporting. Using GPC for water retaining (water tank) is considerable due to excellent autogenous healing behaviour while in Portland cement concrete autogenous healing due to deposition of calcium hydroxide is not desirable.

GPC can be used in light pavements, there is no appearance of bleeding on the concrete surface. Practical example to this, paving a slab for a weighbridge at the Port of Brisbane-2010 with geopolymer concrete (Sathia et al., 2008).

GPC can be used in creating precast bridge decks which provide a serviceable wearing deck, effectively used for the beam-column junction of reinforced concrete structure, in manufacturing reinforced-concrete pipes, for repairing and rehabilitation work (Aleem and Arumairaj, 2012), in marine structure due to its excellent resistance to chemical attacks. It can also be used as water proof, fire proof, and thermal insulator and as retaining wall for a private residence. Geopolymer cement is very suitable to create massive concrete panels, expanded (foam) panels, and fibre reinforced sheet (Davidovits, 1994).

It is also good choice for heat insulation, prestressing, pavements, 3D printing, repairing and rehabilitation work (Aleem and Arumairaj, 2012; Singh et al., 2019). Aleem and Arumairaj (2012) stated that constructing boat ramp in-situ by GPC was better choice than using conventional concrete.

9. Limitations

1. Until now any standard specification to mix design geopolymer system has not been fixed. Because many parameters can affect the system such as curing time, curing temperature, concentration of the chemical liquid, alkali to binder ratio, etc.
2. Geopolymer can be produced only by pre-mixing, thus using high alkalinity chemical solutions such as NaOH is hazardous and has safety risk to humans during mixing and handling, hence it is difficult to create (Safari et al., 2020).
3. In large-scale application, great amount of heat will be released during dissolution of NaOH in water, thus it will be difficult for controlling.
4. The demand for using GPC instead conventional concrete is still limited due to its quality performance.
5. The cost of chemical solution used for activation is very high.
6. Difficulties in applying steam-curing is not practical, especially for large-scale projects.

10. Conclusions

Through reviewing the existing literature, we conclude the following points:

1. GPC is a good alternative to conventional concrete. It becomes an eco-friendly construction material and as a result using cement reduced required energy and CO_2 emissions, utilizing industrial waste materials such as ashes which are widely available.
2. Regarding to the economic aspects, utilizing local source materials helps in reduction of the total cost.

3. GPC can be used in various fields instead of cement-based concrete with providing excellent durability and mechanical properties.
4. Related to the disadvantages, GPC is not recommended to use in mass concrete due to release a huge amount of heat at early stages; and it needs preparation of an alkaline solution at least one day prior, thus it is a time-consuming material.
5. There are possibilities to exhibit drying shrinkages due to high heat-development at early ages and similar to normal concrete GPC is weak in tension. It is very important to improve the behaviour and overcome such weaknesses of the material. Thinking about reinforcing GPC by other materials such as fibres is a good idea to decrease crack propagation and increase the energy absorption capacity.
6. Despite the effective parameters such as concentration, curing time and temperature controlling, all the process from selecting the materials until final stages is necessary to present a perfect production.

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Geopolimerni beton: svojstva, izdržljivost i primena – Pregled

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INFORMACIJE O RADU

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I Z V O D

Beton je jedan od najpouzdanijih, najtrajnijih i najtraženijih građevinskih materijala. Postao je drugi najkorišćeniji materijal posle vode na svetu. Mnoga istraživanja su pokazala da količina ispuštenog CO_2 u atmosferu iznosi 1 tonu tokom proizvodnje 1 tone cementa, što doprinosi 5-7 % ukupnoj emisiji CO_2 u svetu. Geopolimerni beton predstavlja novinu u proizvodnji betona koja ne zahteva upotrebu cementa. Materijali koji se najviše koriste u geopilimeru su nusproizvodi, kao što si leteći pepeo, usitnjena granularna šljaka iz visoke peći, silicijumska prašina i drugi. Industrijski otpadni materijali predstavljaju veliki problem za ljudsko zdravlje, životnu sredinu i nedostatak zemljišta, stoga se njihova ponovna upotreba u proizvodnji geopolimernog betona može smatrati velikom prednošću. Dosadašnje istraživanje pokazuje da većina nusproizvoda pokazuje sličnu ili bolju izdržljivost, kao i mehanička i fizička svojstva u poređenju sa običnim betonom. Zbog toga je geopolimerni beton postao dobar održivi materijal sa mnogo prednosti u odnosu na konvencionalni beton, kao što su visoka brza čvrstoća, odlična otpornost na hemijske napade i koroziju čelične armature, eliminacija očvršćavanja u vodi, niska cena i drugi. Ovaj rad pruža pregled geopolimer betona, njegovog sastava, tipova, trajnosti i posebne primene.

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Social challenges in education for sustainable engineering future - transformative guideline

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ABSTRACT

Engineers are educated and trained to take the lead in sustainable development, tackling worldwide difficulties like depletion of natural resources, contamination, fast-growing populations, and ecological degradation. The relevance of government entities dealing with sustainable development is linked to the societal problem of future education. While all social-economical and/or technical variables play a role in determining the outlook in which each competence originates, novel-adaptive thinking, social intelligence, design mentality, and sense-making, social imagination (cross-sectoral fertilization), cognitive load management, virtual collaboration and networking, and novel media literacy suggest representing crucial drivers for the development of each ability. An extensive selection of continuing education programs enables graduates to improve subject-specific skills and extend their professional networks, with the objective of preparing motivated and highly-trained professionals for the job market. It is feasible to achieve the aim of a sustainable engineering future by recognizing the relevance of these criteria, comprehending, and adequately fulfilling them.

1. Introduction

Nowadays, there are numerous challenges that people face when it comes to the environment, and currently some of them are global warming, loss of biodiversity, food security, sustainable energy supplies, and overuse of resources. There is an urgent need to engage the entire society in order to tackle with the global challenge of climate change. To overcome this existential goal, the advances in environmental, so called - green, technologies, have to be enclosed with the economic value and social attitudes. The distinction of knowledge production and specific-sectoral training system presents important drivers to achieve sustainable development. Environmental education still remains highly specialized and predominantly focused on natural sciences, with socio-political and empowerment aspects only marginally included if at all (Pineda-Martos et al., 2022). Moreover, environmental education in different disciplines focuses on acquiring specialized knowledge and, while this remains essential, fostering knowledge alone, without links to real life, personal experiences, competencies, and values, is insufficient (Hadjichambis et al., 2020).

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Institutional and non-institutional education represents a crucial element in creating a positive impact on environmental behavior. The successful implementation of the European Green Deal must also be carried out through educational system reforms to ensure that all are equipped to meet the challenges of the future, including those related to the labor market (Pineda-Martos et al., 2022). Therefore, 'tailored educational curricula' (Weissbrodt et al., 2020) must contain key competencies and skills needed to support a green economy. Socially and environmentally responsible behaviors may be further reinforced by impermanent education (such as through workplace retraining). Education for the future is a social challenge attached to the importance of public organizations dealing with the environment and climate change.

2. Sustainable engineering practice

2.1. Sustainability - the common denominator

The latest 'State of the environment' report from the European Environmental Agency (EEA) warns that Europe will not meet its 2030 targets unless immediate action is taken in the next ten years to address the 'alarming rate of biodiversity loss'. (European Environment Agency, 2020) Increasing impacts of climate change and the over-consumption of natural resources are present. European countries, leaders, and policymakers are urged to seize the opportunity and use the next decade to radically scale.

The common denominator of society, the environment, and technology - the three fundamental pillars of the circular economy - is presented via multidisciplinary and application-oriented research in conjunction with partners from industry, science, and administrative agencies. (Velenturf and Purnell, 2021)

2.2. Circular economy

Circular economy in Europe: insights on progress and potential, a recent European Environment Agency research, showed that investment in upscaling innovative technologies and tracking progress toward circularity will aid circular economy projects in Europe. According to the survey, European businesses are constantly embracing circular business models, with an emphasis on operational efficiency and waste reduction. Moving away from product-based business models and toward provider, company models are also considered a promising trend. According to the survey, 21 of the 32 EEA member countries that responded supported corporate sustainability proposals, which included the use of regulation and market-based instruments for recycling, energy recovery, and waste management, as well as softer policy instruments like labeling requirements and awareness-raising for green building, utilization, and reusability. (Ozturk, 2019) Many crucial data, such as manufacturing and supply stages of the production process life cycles, are not obtainable in existing systems engineering, particularly government data, according to the research. It also emphasizes the importance of integrating corporate sustainability policies and efforts with bioeconomy and climate policies. The textile industry is mentioned as a large water user, while the surface and groundwater sector is emphasized as a substantial source of waste flows. Small to medium-sized businesses throughout the European continent were seen to be lowering material and water use, mostly to save inner manufacturing costs. (European Environment Agency, 2016)

2.3. Internationalization

These socio-economical and environmental challenges require a global approach involving cooperation between countries and researchers around the world. Exchange programs for students and staff are an important way of establishing and strengthening collaboration. The experience from different countries provided by these programs leads to a broader general understanding of society and the environment. The professional and methodological skills are expanded, and their social and personal competencies are developed, making it easier for students to start on their career paths. Students can be helped to better integrate their concepts into the work by incorporating fundamental skills and understanding through educational internship opportunities. (Tynjälä, 2008) A further bonus is an improvement in foreign language skills.

2.4. Research-relevant specialization

The primary focus is on sustainable research, development, and services. They are able to answer complicated challenges due to the wide range of themes and tight collaboration between research units and other universities. Collaboration with the federal government, municipalities, private enterprises, and commercial partners is critical to ensuring the social relevance of their programs and promoting their practical execution. Furthermore, Engineers Without Borders has launched Community Engineering Corps to handle environmental, power, structural, and civil engineer concerns for areas that cannot afford professional technical and engineering advice. (CEC, 2022)

2.5. Individual professional specialization

Nowadays, living in harmony with nature is of utmost importance, which at the same time requires responsible action – not only to satisfy our own demands but also in the interest of future generations. The goal is to prepare motivated and highly-trained specialists for the labor market, where the wide range of continuing education programs enable graduates to develop their subject-specific skills and expand their professional networks.

2.6. Interdisciplinarity

Unfortunately, one of the current deficiencies related to interdisciplinary is that formal education systems limit communication between different experts. In order to compensate for this deficiency, it is necessary to educate a new generation of professionals and improve the ability of professionals to communicate with different experts and lay communities. One of the conditions for the emergence of modern types of interdisciplinary pedagogies is the formation of educational groups that combine different types of knowledge or sciences (for example, social, ecological and biological sciences). The development of this approach, which includes experiential learning and the collaboration of pedagogues and students from different fields, enables future experts to respond to the complex challenges posed by climate change and the lack of implementation sustainable development in practice.

2.7. Monitoring the impact

To promote sustainable innovations and entrepreneurship in the fields of society, environment, and technology, the main pillars have to be gathered in the following direction:

- Society as a hub for environmental and sustainable issues. Through its behavior, society not only influences production methods and innovation efforts but also dictates the transformative guidelines and further political agenda;
- The environment as a living space and a uniform reflection of society. People change the environment, resulting in the common changes that affect society both directly and indirectly;
- Technology as a human instrument and an important factor that influences the environment. Societal and political portfolios indicate how technological developments are driven forward (conventional towards green solutions, and vice versa) and used, and thus also have an effect on resultant consequences.

3. Future work skills 2020

While all social-economical and/or technological drivers are important in shaping the landscape of future engineering skills, these skills have particular relevance for education in sustainable engineering future:

1) Novel-adaptive thinking;
2) Social intelligence;
3) Design mindset and Sense-making;
4) Social imagination (cross-sectoral fertilization);
5) Cognitive load management;
6) Virtual cooperation, networking; and
7) Novel media literacy.

3.1. Novel adaptive thinking

Rather than being inert beneficiaries of the unavoidable transformation that is emerging in this ongoing period, it is important for society to be the one that directs this transformation for the sake of societal structure and coming generations. To provide it, it is necessary to be adaptive, i.e. to recognize that what has happened in history may not ensure success in this fast-paced transformation phase that will shape tomorrow. According to Kolb, an individual's ability to adjust and evolve during their lifetime is strongly influenced by their capacity to react proficiently to changes. (Kolb et al., 2001; Kolb and Kolb, 2009) "Adaptive flexibility" is the term for this capability. Individuals with a high degree of adaptive flexibility may quickly alter their learning algorithm to the needs of the scenario. (Duchesne, 1997)

3.2. Social intelligence

According to Al-Janabi, the capacity to comprehend and engage with people, and analyze and adjust their behaviors in order to attain personal and social advantage represents social intelligence. (Al-Janabi, 2019) The engineering faculty's major mission is to educate qualified engineers for the local economy. Academic institutions play an important role in the construction and refining of an engineer's consciousness, in terms of providing academic education. Hanbazazah stated that the three skill categories with the lowest ratings are likely the most significant in the work area: cooperation, conflict resolution, and social adaptability. (Hanbazazah, 2020)

Social skills such as emotional intelligence, creative perspectives, and integration in interdisciplinary backgrounds will facilitate us to maneuver through the pace of the fast global cultural evolution in a fair and green manner as machine learning, robotics, and biotechnology become more prevalent in the job market. Hard skills may be acquired, but it is the approach, perspective, and capacity to work successfully with one another as individuals that distinguish us from computers with formulas and programs.

3.3. Design mindset and Sense-making

It is critical to foster an engineering mentality that emphasizes the necessity of having a sense of creativity, as this is a primary consideration for future engineers.

Skill sets that may be learned via interdisciplinary education where human and social sciences comprehend science and technology and vice versa are highly necessary in order to thrive in The Fourth Industrial Revolution. Furthermore, because vision, imagination, and flexibility are not readily computerized qualities, prospective students and engineers need to nurture these characteristics in order to succeed in a progressively mechanical world. Asunda et al. have reported a study related to critical features of engineering design in technology education based on interviews with professors fully engaged in engineering education, but also supporting documentation. Professors should search out efficient strategies to assist their students to focus and engage in the planning phase and the utility of issue answers, according to the findings. These competencies can aid students to develop skills to solve the issues they confront on a constant schedule. (Asunda and Hill, 2007)

3.4. Social Imagination

Mills defined social imagination as a state of mind that allowed one to comprehend history and biography, as well as their interrelationships within society that every human should adopt. (Mills, 2000) While explaining the importance of social intelligence for engineers, it is crucial to note that technical practice does not take place in a bubble. Instead, it takes place in social circumstances that influence engineers' way of thinking and their decisions. In other words, engineering practice is based on creating an easier, better life for humans but also considering sustainability factors. Social factors that impact engineering issue creation and solving problems, on the other hand, are mostly unseen to individual engineering students. (Johnson et al., 2015) Academic education does not provide enough engineering students with the knowledge and skills needed in engineering practice. However, implementing social imagination basics in engineering studies or any other has a role to reveal social factors that shape the behavior of future engineers in practice. This way, future engineers are more likely to be encouraged, self-assured, motivated, and engaged, but also creative when transferring the acquired knowledge into practice. (Leydens et al., 2021)

3.5. Cognitive load management

The origins of cognitive load theory may be traced back to educational studies. It is assumed that learning entails a cognitive load that is restricted by working memory capacity. Dias et al. have explained the word "cognitive load" as a combination of factors such as cognitive stress, mental strain, and mental effort. (Dias et al., 2018) The most straightforward explanation for the significance of these elements stems from the simple truth that greater efficiencies and performance with increasing cognitive load up to a degree. However, overtraining sets in after this and the result is a reduction in performance quality. Low cognitive load leads to a state of undertraining and, as a result, a drop in performance. (Zimmerer and Matthiesen, 2021)

It is critical to maintain control in this manner by concentrating on the learning phase, the student, and the learning process. Having to learn from disparate pieces of knowledge necessitates more selective attention movement, making the mental consolidation required to comprehend the learning activity more challenging than acquiring from a single source. In addition, inexperienced learners understand more by examining completed cases with solutions than by addressing identical issues. While struggling to understand tasks through critical thinking, on the other hand, students devote the majority of their capacity to implementing the solution approach, resulting in greater unnecessary mental demand and, as a result, almost no educational material. As noted, this theory is related to inexperienced, young students. However, students with more knowledge and experience often do not need already solved repetitive problems, but new unsolved problems to gain more experience. Paas has stated that learners should work together on educational activities to maximize accessible cognitive capabilities, transfer data related to other methodologies, or put more effort into the activity. (Paas and van Merriënboer, 2020)

3.6. Virtual cooperation, networking

According to Shirado and Christakis, the significance of cooperation in human societies is complex, and multiple methods are necessary to maintain it, despite the fact that it frequently regresses over time. (Shirado and Christakis, 2020) Online technology has had little importance in this education until recently, but it can no longer be regulated now without it.

Today, multimedia education is getting a lot of traction as a result of the growing users of digital technology along with the Corona pandemic that drastically altered collaborative practices. The new educational methodology encourages education in a variety of settings, and is, therefore, therefore an important aspect in improving teaching and learning regardless of the learner's circumstances or geographic area. As a result, it offers a genuine learning environment in which students may establish interconnections to the actual world while studying. (Curum and Khedo, 2021) Although the implementation is carried out by participants may be varied, networking shares knowledge, skills, and resources across locations for the mutual benefit of all participants. Networks can bring participants from many sectors or levels of the educational system to each other to pool their combined experience, i.e. all parties must recognize the benefit of becoming a member of the cloud infrastructure for it to work well. All performers profit, but not at the price of anyone else's advantage.

3.7. Novel media literacy

The advancement of technology and its incorporation into all aspects of people's lives has made it possible for the first time to have instant and unrestricted access to massive amounts of information that is continually enriched, altered, and updated. Including its participatory and more personalized online content, the Digital revolution media communication technologies modified people's routines and behavior, creating a new method for attaining key cues. They are quickly becoming a popular indispensable provider of instruction and a vital instrument for the establishment of innovative reading skills. No other education tool has been embraced by so many people, in so many diverse areas, in such a short amount of time, and with such far-reaching repercussions. (Kumar, 2020) However, new media literacy, as defined by Koc and Barut, is a notion that encompasses a set of critical abilities such as critiquing, generating, and engaging in 'technology-based socio-cultural platforms', as well as aspects of the ubiquitous computer environment. (Koc and Barut, 2016)

Today, young engineers and scientists use social media sites like LinkedIn, Research Gate, and Google Scholar to share their knowledge with the scientific community and possible employers. Certainly, there are many more people who are governed by the old way of thinking and have not yet encountered the social networks that the new century has delivered. This is especially true of elder generations, while younger generations are progressively becoming involved and building their own base, allowing them to obtain new experiences while also sharing old ones with colleagues all over the world. As indicated by the growing interest in social networking in the digital realm, new media literacy is evolving. However, more work is required in the near future to accurately estimate current recent advancements in social media in relation to engineering students.

4. Conclusions

Sustainable development guarantees that socio-economical, and ecological structures are not jeopardized, preserving both the micro-and macro quality of life as well as the viability and range of environmental surroundings. In terms of sustainable development, education, both formal and informal, is a critical component in influencing environmental behavior in a good way. Today, in order to stay up with the fourth Industrial Revolution, the right circumstances must be in place to assure long-term development. Future engineers must have particular attributes and talents in order to usher in a new age of technological advancements. These elements are related to novel adaptive thinking, which is defined as the introduction of new techniques for solving issues based on faculty knowledge, as well as thinking outside the box.

Other factors include finding deeper meaning in negative issues, connecting with other experts from related and unrelated fields who can help solve puzzles in person, developing social intelligence, not retreating to their own hidden world, and utilizing new platforms on social networks that will enable the exchange of information among engineers around the world. In this approach, a more comprehensive view of global sustainability, engineering practice, and the application of innovative ideas to tackle current and future challenges may be obtained. Certainly, achieving the required sustainability will take a lot of effort and labor, but the reason for doing so should be a brighter tomorrow for us and future generations.

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Društveni izazovi u obrazovanju za budućnost održivog inženjerstva – transformativne smernice

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I Z V O D

Inženjeri se obrazuju i obučavaju da preuzmu vođstvo u održivom razvoju i da se bore sa problemima širom sveta, kao što su iscrpljivanje prirodnih resursa, kontaminacija, porast populacije i ekološka degradacija. Relevantnost državnih organa koji se bave održivim razvojem povezana je sa društvenim problemom budućeg obrazovanja. Dok sve društveno-ekonomske i/ili tehničke varijable igraju ulogu u određivanju perspektive iz koje svaka kompetencija potiče, prilagodljivo razmišljanje, socijalna inteligencija, kreativno razmišljanje, davanje smisla, društvena imaginacija (međusektorska fertilizacija), upravljanje kognitivnim opterećenjem, virtuelna saradnja i umrežavanje, kao i nova medijska pismenost predstavljaju ključne pokretače za razvoj svake sposobnosti. Veliki izbor programa kontinuiranog obrazovanja pruža mogućnost onima koji su diplomirali da unaprede veštine specifične za njihovu oblast i prošire svoje profesionalne mreže, a sa ciljem da se motivisani i obučeni stručnjaci pripreme za tržište rada. Moguće je postići cilj omogućavanja održive inženjerske budućnosti tako što će se prepoznati važnost ovih kriterijuma, omogućiti njihovo razumevanje i ostvarivanje.

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Municipal Solid Waste-to-Energy in EU-27 towards a Circular Economy

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ABSTRACT

The current work deals with the energy recovery, through incineration (R1) and biological treatment (R3), from municipal solid waste (MSW), within EU-27 in a Circular Economy approach. The EU legislation is analyzed in reference to the production and management of MSW for energy recovery along with the Waste-to-Energy processes (Incineration, Anaerobic Digestion and Composting, Pyrolysis, Gasification, Plasma technology, and Landfill gas). As reference years, 2015 and 2019 have been considered, which are the corresponding years of the first European plan towards a Circular Economy (COM - (2015) - 614) and the year before COM-(2020)-98. Also, the following data have been collected and elaborated from each Member State for the years 2015 and 2019: the total MSW generated, the total MSW used for energy recovery through incineration and biological treatment, the primary energy production from renewable and non-renewable MSW, and the gross domestic energy consumption by MSW-generated energy. The main conclusion drawn from this work was the growing trend of the quantities of MSW used for energy recovery in EU-27 and the increasing trend of primary energy production from MSW that EU followed as aggregate. It was observed that for some Member States, energy followed increasing trend, of higher or lower rate, while for other showed descending trend. Despite the overall increasing trend of energy production from MSW, the rate is still relatively low, at least for some countries, and greater effort is required for their compliance with EU policy towards a Circular Economy approach.

1. Introduction

High levels of environmental pollution, overexploitation of resources, water and land pollution are subjects of main concern worldwide. The huge production of waste, combined with the inefficiency of their management, works negatively in reference to the improvement of living standards and achievement of sustainable development. It is therefore necessary to reduce waste production as much as possible and increase their management level. Given that the overconsumption of resources continues, waste production is expected to increase by 70 % until 2050 (COM-(2020)-98). As a result, the situation must be addressed immediately, in order to conserve resources and reduce the amount of waste generated. For this reason, the European Commission suggested the EU action plan for Circular Economy, on 2 December 2015. Circular Economy is characterized by an innovative economic system, which is totally different from the linear economy (produce - consume - reject), as the value of the products remains in the economy and resource utilization is maintained to a minimum (COM-(2015)-614). As it is referred in this action plan, the transition to the Circular Economy will

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be an opportunity for the European Economy to transform and for Europe to gain new, sustainable competitive advantages (COM-(2015)-614). It is important to note that the relationship between the concepts of Circular Economy and Sustainability is not clear and efforts are being made through the existing literature to clearly define their similarities and differences (Geissdoerfer et al., 2017).

In 2018, four new Directives (2018/849, 2018/850, 2018/851, 2018/852) on solid waste were legislated by the European Union, in which the term "Circular Economy" appeared for first time. These new Directives have set higher targets in terms of recycling, separation at source and diversion of waste from landfilling (Komilis, 2020). No later than 31 December 2030 a minimum of 70 % by weight of all packaging waste must be recycled (Directive 2018/852/EU). By 2025, 2030, and 2035 the preparation for re-use and recycling of municipal waste should be increased to 55 %, 60 %, and 65 % by weight, respectively (Directive 2018/851/EU). By 2035, the amount of municipal waste ending up in landfills should be 10 % by weight or even less of the total amount of municipal waste generated (Directive 2018/850/EU). According to the European Commission (2021), "The EU aims to be climate-neutral by 2050 - an economy with net-zero greenhouse gas emissions". To achieve this target, the waste hierarchy must be respected. According to the Directive 2008/98/EC of the European Commission, the following waste hierarchy "shall apply as a priority order in waste prevention and management legislation and policy": i) prevention, ii) preparing for re-use, iii) recycling, iv) other recovery, e.g., energy recovery, and v) disposal (Directive 2008/98/EC). It is obvious that Waste-to-Energy (WtE) is the last option before landfilling of non-recyclable waste. This method of waste treatment has some serious benefits over landfilling such as the destruction of pathogens, the reduction of greenhouse gas emissions, the recovery of metals, etc. (Bourtsalas and Themelis, 2017). WtE technology has also a lot of benefits contributing to a Circular Economy. Energy production from waste can prevent the production of 50 million tons of carbon dioxide produced using fossil fuels (Levaggi et al., 2020). For example, in 2015, 90 million tons of waste in the EU was thermally treated at WtE facilities generating 90 TWh of heat and 40 TWh of electricity, saving 50 million tons of fossil fuels, and avoiding the production of 49 tons of carbon dioxide (CEWEP, 2021). With this method of waste treatment, energy can be produced either in the form of fuel or electricity and/or heat. WtE can also contribute to the reduction of the amount of waste, which is landfilled; hence, the production of methane is reduced too. In addition, recovery of metals from the bottom ash, left after incineration, is also possible. Effective source separation can prevent the entrance of recyclable waste (e.g., plastics) in WtE plants, reducing in this way the CO_2 emissions (CEWEP, 2021). This is sustained by Quina et al. (2011) whose research on the health impact of emissions from municipal solid waste incineration revealed that no health problems can be related to modern incinerators for MSW.

In 2017, the Document of European Commission COM-(2017)-34, about the role of waste to energy in a Circular Economy, was presented based on COM-(2015)-614. Communication (2017)-34 of the European Commission focuses on energy recovery from waste and its position in the Circular Economy. This document covers the following five WtE processes:

<u>Co-incineration of waste in incineration plants, as well as in the production of cement and lime (COM-(2017)-34).</u> According to a relevant study (Galvez-Martos et al., 2014), it was observed that with the use of waste-derived fuels, instead of fossil fuels, a large part of the emission becomes biogenic; simultaneously, the co-incineration of waste-derived fuels in cement plants may be linked with energy loss, which can neutralize the benefit of replacing carbon dioxide from fossil fuels with biogenic carbon dioxide from waste. Reducing the clinker factor can significantly help reduce carbon dioxide emissions and be more effective than substituting fossil fuels for waste-derived fuels. <u>Incineration of waste in special facilities (COM-(2017)-34).</u> In this case, special facilities are used for the incineration of municipal solid waste, where the plants have higher energy efficiency (R1) of 0.6 and 0.65, as will be discussed in more detail in the present work.

<u>Anaerobic digestion of biodegradable waste (COM-(2017)-34).</u> Organic waste (proteins, carbohydrates, fats) is converted by hydrolysis to soluble organic molecules (amino acids, sugars, and fatty acids, respectively); then, through the generation of acids (acidogenesis) a part of the hydrolysis products is converted directly to acetic acid, hydrogen, and carbon dioxide. The part of the products from acid production that has not been properly converted, i.e., the intermediate products (butyric acid, propionic acid, etc.), are subjected to the production of acetic acid (acetogenesis), in which only acetic acid, hydrogen, and carbon dioxide are produced in this process. The last process is the generation of methane (methanogenesis), through which acetic acid, hydrogen, and carbon dioxide are converted to methane and carbon dioxide (Abdelgadir et al., 2014; Tsekeris, 2021;). Pre-treatment of biomass before anaerobic digestion is mandatory to improve the biodegradability of the raw material and produce enhanced biogas. According to a recent research (Varjani et al., 2022), the physicochemical pretreatment method has benefits in enhancing hydrolysis throughout the digestion of waste biomass.

<u>Production of solid, liquid, and gaseous fuels from waste (COM-(2017)-34).</u> Since prevention, reuse, and recycling are preferable to WtE, more emphasis should be placed on the above-mentioned waste management processes and more research should be carried out on

other types of raw materials that can be converted into fuels. Lignin, for example, is a key raw material of high interest where efficient methods have been developed for its conversion into various forms of biofuels (solid, liquid, and gaseous). Although methods of converting lignin to biofuels have evolved, more research is needed in order to meet energy needs in the future (Suresh et al., 2021).

Other processes involving indirect incineration after the pyrolysis or gasification stage (COM-(2017)-34). Pyrolysis is a well-known waste management process and is characterized as the process of thermal decomposition of solid fuels, which takes place in environment with absence of oxygen or under conditions of limited oxygen; the final products are gases (carbon dioxide, methane, hydrogen, etc.), liquids (a mixture of oily form of high viscosity and density consisting of oxygenated hydrocarbons, methanol, acetone, and acetic acid) and solids (residue consisting of almost solid carbon) (Tchobanoglous and Kreith, 2002). Relevant research conducted (Reza et al., 2022) shows that the pyrolysis of fish waste (bluespotted stingray) can be an important source of biofuels, which makes this category of waste as a good alternative energy source. Regarding gasification, it is one of the thermal conversion processes available for the thermal treatment of solid waste. Gasification of biomass is a process of incomplete combustion (partial presence of oxygen) of biomass, resulting in the production of fuel gases consisting of hydrogen, carbon monoxide and methane (Rajvanshi, 1986; Belgiorno et al., 2003; Tsekeris, 2021). It seems that co-gasification using two raw materials is more beneficial than simple gasification in terms of better process efficiency as well as tar formation (Yang et al., 2021). Recently, the production of hydrogen-enriched syngas through a combined gasification pressurized system, which is being investigated in a novel integration with geothermal energy, has aroused interest (Gungor and Dincer, 2022).

These processes have different environmental impacts; therefore, they have a different rank in waste hierarchy. For example, incineration and co-incineration with limited energy recovery are considered as disposal (D10). On the contrary, incineration and co-incineration with high energy recovery are considered as recovery (R1). Regarding anaerobic digestion of organic waste, it is considered as recycling (R3) (Directive 2008/98/EC; COM-(2017)-34). According to the Document COM-(2017)-34 of the European Union, the most efficient methods of energy recovery from waste are listed below (Komilis, 2020):

i. upgrading of biogas into bio-methane for further distribution and use,
ii. gasification of solid recovered fuel (SRF) and combustion of the produced gaseous fuel to replace fossil fuels in thermal and electric power plants,
iii. co-existence of waste incineration plants with neighboring industries with the former targeting to waste management of the latter while they will provide heat and electricity to the industry that produces waste,
iv. co-incineration of waste together with fossil fuels for the production of lime and cement and preference for the operation, and
v. construction of combined heat and power (CHP) waste incineration plants because they achieve higher energy efficiencies than the types of municipal solid waste incinerators that recover only electricity or only heat.

The European Commission anticipates by applying these processes, it is possible for the amount of energy recovered from waste to rise by 29 % using the same amount of waste (COM-(2017)-34). It seems that the energy recovery from waste can contribute to the promotion of the Circular Economy, through reducing the volume of waste generated, while, at the same time, generating energy and reducing greenhouse gas emissions. It is important to note that energy recovery from waste is preferred from landfill only, according to waste hierarchy, as prevention, reuse, and recycling are of major priority. Waste-to-energy is a widespread method of waste treatment, and it is widely applied both in Europe and other countries. Although WtE has some benefits in establishing a Circular Economy, as described above, there are two main negative factors that need to be considered. The first major negative factor in municipal solid waste incineration is the production of negative carbon dioxide because part of carbon in waste is biogenic (Wienchol, 2020). As for the second dangerous feature, it is the hazardous fly ash and the residues left after incineration (Quina et al., 2011).

The current study deals with the subject of energy recovery from municipal solid waste (MSW) in a Circular Economy and the corresponding activity of EU Member States in this regard. To clarify, the term waste-to-energy denotes the processes of thermal treatment (Incineration with energy recovery, Pyrolysis, Gasification, and Plasma technology), biological treatment (Composting and Anaerobic Digestion), and landfilling (Landfill gas) (Kumar and Sammader, 2017; Komilis, 2020). As the most of Waste-to-Energy processes have been analyzed above, it is important to explain the plasma technology for a complete picture of the WtE operations. During the plasma technology, municipal solid waste is converted to gases and to an inert solid residue; it is reported that this method of waste treatment is still in the experimental stage for MSW (Komilis, 2020). Regarding composting, it is discussed in more detail further in this work. WtE is one of the most common methods used for MSW (Psomopoulos et al., 2009). Therefore, in this study, an attempt has been made to approach the issue, based on statistics, in order to determine the changes brought about by the Circular Economy, in terms of MSW quantities used for energy recovery through incineration with energy recovery (R1) and biological treatment (R3) by the Member States, for the years before and after the implementation of the Circular Economy, namely 2015 and 2019; it must be pointed out that the data for each one of EU-27 Member States have been collected and elaborated by the authors of the current work.

2. Materials and Methods

2.1. Municipal Solid Waste

In this study, data was collected for each one Member State regarding the production of the total municipal solid waste, the portion of generated MSW used for energy recovery (incineration (R1) and biological treatment (R3)), the amount of primary energy produced and the gross inland energy consumption by MSW-generated energy for the years 2015 and 2019.

In the category of municipal waste, mixed waste, separately collected waste from households (e.g., textiles, packaging, glass, waste electrical and electronic equipment, bulky waste, metals, plastics, bio-waste, wood, paper, and cardboard) and separately collected waste from other sources of similar nature and composition to the waste from households were included. Waste from forestry, agriculture, fishing, production, septic tanks and sewage network, and treatment was not included in the category of municipal waste. Also, waste such as end-of-life vehicles, wastes from construction and demolition, sewage sludge were not included (Directive 2018/851/EU).

2.2. Municipal Solid Waste generation in EU-27 in 2015 and 2019

Municipal waste accounts for approximately between 7 and 10 % of total waste generated in the EU (Directive 2018/851/EU). For example, the total waste production in 2018 was 2336.7 million tons (Mt), out of which the total municipal waste produced for the same year was 221.61 Mt (Eurostat, 2021). Therefore, the percentage of municipal waste was about 9.48 % of the total. This category of waste is too difficult to be managed due to its complex and mixed composition. Consequently, it requires effort from citizens and enterprises to achieve higher management level (Directive 2018/851/EU). Table 1 shows the quantity of municipal solid waste generated in 2015 and 2019 and the percentage of change between these years in the EU-27 (Eurostat, 2021).

Table 1
EU-27: Municipal Solid Waste generated, 2015-2019 (Million tons)

	2015	2019	% Change 2019/2015
EU-27	213.409	224.447	5.17
Belgium	4.643	4.779	2.9
Bulgaria	3.011	2.862 (2018)	-4.94 (2015-2018)
Czech Republic	3.337	5.338	59.96
Denmark	4.671	4.907	5.05
Germany	51.625	50.612	-1.96
Estonia	0.473	0.49	3.59
Ireland	2.763 (2016)	2.912 (2018)	5.39 (2016-2018)
Greece	5.277	5.613	6.36
Spain	21.158	22.438	6.04
France	34.344	36.74	6.97
Croatia	1.654	1.812	9.55
Italy	29.524	30.023	1.69
Cyprus	0.525	0.566	7.8
Latvia	0.798	0.84	5.26
Lithuania	1.3	1.319	1.46
Luxembourg	0.346	0.491	41.9
Hungary	3.712	3.78	1.83
Malta	0.285	0.35	22.8
Netherlands	8.866	8.806	-0.67
Austria	4.836	5.22	7.9
Poland	10.863	12.753	17.39
Portugal	4.769	5.281	10.73
Romania	4.904	5.43	10.72
Slovenia	0.926	1.052	13.6
Slovakia	1.784	2.299	28.86
Finland	2.738	3.123	14.06
Sweden	4.422	4.611	4.27

As it can be observed from Table 1, there are huge differences in municipal solid waste generation between the Member States. According to the analysis made by the authors, this is due to the huge variations observed in the production of municipal solid waste (in kg per inhabitant). Combining the results of the analysis with a recent survey (Minelgaitė and Liobikienė, 2019), it seems that the level of municipal solid waste production depends significantly on the economic development of each Member State. Therefore, in the most economically prosperous countries there is production of more municipal solid waste per inhabitant, thus contributing to the production of large quantities of MSW in these countries (e.g., Denmark, Germany, etc.).

2.3. Municipal Solid Waste management in EU-27 in 2015 and 2019

Figure 1 shows the quantity of MSW that was managed in the EU-27 for the years 2015 and 2019. The generated MSW was subjected to either disposal (D) or recovery (R) operations. The 1st pair of bars in Figure 1 refers to the amount of MSW which was treated. The 2nd and 3rd pairs of bars refer to the amount of MSW that was subjected to disposal operations. In the 2nd pair of bars the following operations were included: the disposal operations D1 (deposit into or on to land), D2 (land treatment), D3 (deep injection), D4 (surface impoundment), D5 (specially engineered landfill), D6 (release into a water body), D7 (release to seas/oceans), and D12 (permanent storage) (Directive 2008/98/EC). The 4th, 5th and 6th pairs of bars refer to the amount of MSW that was subjected to recovery operations. In the last pair of bars, the amount of MSW that was generated but not managed (uncontrollable rejection) is presented (Eurostat, 2021). Figure 1 presents the municipal solid waste management in the European Union. It is interesting to refer to the conclusions of a study (Minelgaitė and Liobikienė, 2019), according which, despite the increasing level of prevention and reuse of MSW, no significant impact on their generation was observed.

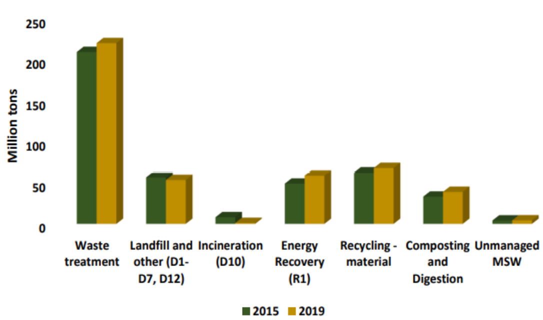

Figure 1. EU-27: Municipal Solid Waste management in 2015 and 2019

By considering 2010 (Eurostat, 2021) as reference year (instead of 2015), huge improvement over a period of nine years (2010-2019) is observed, in terms of the quantity of waste incinerated without energy recovery (D10) in the EU-27 (Eurostat, 2021). This quantity was about 13.105 million tons (Mt) and 1.121 Mt in 2010 and 2019, respectively (decrease by -91.44 %). For example, a great reduction of the quantity of MSW incinerated without energy recovery was observed in Germany (from 10.534 Mt in 2010 to 0.484 Mt in 2019). The rate of this reduction was about -95.4 %. The Netherlands reduced this amount from 1.833 Mt (2010) to 0.095 (2019) (- 94.81 % reduction). Also, in France the amount reduced from 0.42 Mt (2010) to 0.069 Mt (2019) or by -83.57 % (Eurostat, 2021). This study deals with the energy recovery from MSW through incineration (R1) and biological treatment (R3) in the EU-27 in 2015 and 2019. Tables 2 and 3, in the following sections 2.4 and 2.5, show the amount of MSW incinerated with energy recovery (R1) and the amount of MSW biologically treated (R3, Composting and digestion).

2.4. Incineration (R1) of Municipal Solid Waste with energy recovery, in EU-27, in 2015 and 2019

The recovery operation R1, which is defined as the "use of waste mainly as a fuel or as another means of generating energy", includes the incineration facilities dedicated to the processing of MSW only if their energy efficiency is equal to or higher than:

i. 0.60 for installations licensed before 1 January 2008 and
ii. 0.65 if licensed after 31 December 2008 (Directive 2008/98/EC).

According to a survey conducted in 2010 (Grosso et al., 2010), the distribution of plants dedicated to the processing of MSW in Europe was:

i. 43.5 % of MSW plants have energy efficiency higher than 0.65,
ii. 13.5 % of MSW plants between 0.60 and 0.65, and
iii. the remaining 43 % lower than 0.6, namely without energy recovery.

According to data obtained from CEWEP (2021) and Scarlat et al. (2019), the number of WtE plants differs significantly between the Member States. There are 121 WtE plants in France, followed by Germany (96), Italy (38), Sweden (37), Denmark (26), Belgium (17), The Netherlands (12), Spain (12), Austria (11), Finland (9), Poland (7), Czech Republic (4), Portugal (4), Slovakia (2), Ireland (2), Estonia (1), Lithuania (1), Hungary (1), Luxemburg (1), and Malta (1).

Before referring to the quantities of MSW incinerated with energy recovery, it is important to mention a characteristic of waste that plays a vital role in their incineration, known as heating value. Heating value is defined as the amount of energy generated from the complete combustion of a fuel; it can be expressed either as higher heating value (or higher calorific value), in which the latent heat of evaporation of water is included, or lower heating value (or net calorific value), in which the latent heat of evaporation of water is not included (Anastassakis, 2001). A recent survey carried out by Taki and Rohani (2022) concluded that the machine learning method, known as Radial Bias Function Artificial Neural Network, could predict the higher heating value of municipal solid waste more accurately in comparison with other models. The heating value of MSW ranges between 8 MJ/kg (Megajoule/kilogram) and 14 MJ/kg (Themelis et al., 2013). The average heating value of MSW is about 10 MJ/kg. For this reason, municipal solid waste is used for energy production (Malinauskaite et al., 2017). One ton of MSW, with heating value of 10 MJ/kg, produces thermal energy of approximately 2.78 MWh (Themelis et al., 2013). According to the International Energy Agency (IEA), 1 ton of oil equivalent (toe) or 1.429 ton of coal equivalent equals to the production of 11.63 MWh (IEA, 2021), which means that about four tons of municipal solid waste with heating value of 10 MJ/Kg equals to 1 ton of oil or 1.429 tons of coal. Generally, if a waste possesses heating value lower than 2.32 MJ/kg (e.g., stones, concrete blocks, etc.), it is considered unsuitable for incineration. Waste to be incinerated are wood, paper, rubber scraps, cartons, plastic scraps, rags, garbage and rubbish, vegetal and animal waste, etc. (Tchobanoglous and Kreith, 2002) In order to determine the capacity for the incineration of waste, the following five factors are taken into account:

i. the heating value,
ii. the moisture content of waste,
iii. the inorganic salts,
iv. the radioactive wastes, and
v. the high content of halogens or sulfur (Tchobanoglous and Kreith, 2002).

Table 2 shows the quantity of MSW incinerated in 2015 and 2019 in the EU-27 and the percentage change between these years (Eurostat, 2021).

2.5. Biological treatment (R3) of Municipal Solid Waste (Composting and Anaerobic Digestion) in 2015 and 2019, in EU-27

Table 3 shows the quantity of MSW that was biologically treated (R3) in the EU-27 in 2015 and 2019, through composting and digestion (Eurostat, 2021). Composting is a biological process of degradation and stabilization of organic materials. This procedure consists of three basic processes regarding the MSW:

Table 2
EU-27: Municipal Solid Waste incinerated with energy recovery, 2015-2019 (Million tons)

	2015	2019	% Change 2019/2015
EU-27	48.972	58.62	19.7
Belgium	2.014	2.021	0.34
Bulgaria	0.082	0.208 (2018)	153.6 (2015-2018)
Czech Republic	0.586	0.868	48.12
Denmark	2.396	2.333	-2.62
Germany	12.068	15.98	32.41
Estonia	0.243	0.221	-9.05
Ireland	0.811 (2016)	1.243 (2018)	53.26 (2016-2018)
Greece	0.018	0.074	311.11
Spain	2.685	2.533	-5.6
France	11.957	12.461	4.21
Croatia	0	0.001	-
Italy	2.969	5.711	92.35
Cyprus	0	0.005	-
Latvia	0.015	0.028	86.66
Lithuania	0.15	0.194	29.33
Luxembourg	0.156	0.229	46.79
Hungary	0.525	0.515	-1.9
Malta	0.004	0	-
Netherlands	4.057	3.577	-11.83
Austria	1.833	2.004	9.32
Poland	1.318	2.742	108.04
Portugal	0.941	0.996	5.84
Romania	0.116	0.251	116.37
Slovenia	0.158	0.136	-13.92
Slovakia	0.191	0.125	-34.55
Finland	1.312	1.735	32.24
Sweden	2.284	2.427	6.26

Table 3
EU-27: Municipal Solid Waste biologically treated (composting and digestion), 2015-2019 (Million tons)

	2015	2019	% Change 2019/2015
EU-27	33.122	38.946	17.58
Belgium	0.9	0.982	9.11
Bulgaria	0.311	0.052 (2018)	-83.27 (2015-2018)
Czech Republic	0.141	0.602	326.95
Denmark	0.858	0.882	2.8
Germany	9.298	9.442	1.54
Estonia	0.017	0.012	-29.41
Ireland	0.19 (2016)	0.245 (2018)	28.94 (2016-2018)
Greece	0.135	0.283	109.62
Spain	2.452	3.751	52.97
France	6.186	7.394	19.52
Croatia	0.028	0.063	125
Italy	5.203	6.387	22.75
Cyprus	0.018	0.008	-55.55
Latvia	0.047	0.042	-10.63
Lithuania	0.132	0.293	121.96
Luxembourg	0.063	0.094	49.2
Hungary	0.231	0.353	52.81
Malta	0	0	0
Netherlands	2.414	2.569	6.42
Austria	1.511	1.677	10.98
Poland	0.611	1.153	88.7
Portugal	0.745	0.883	18.52
Romania	0.365	0.239	-34.52
Slovenia	0.071	0.176	147.88
Slovakia	0.13	0.269	106.92
Finland	0.341	0.442	29.61
Sweden	0.684	0.653	-4.53

i. processing of the MSW,
ii. decomposition of the organic MSW, and
iii. preparation of the final compost (Hamoda et al., 1998).

This final product can be used as soil fertilizer. Regarding anaerobic digestion, it is also a biological waste process, which provides with biogas and a final solid residue (digestate) with potential fertilizer characteristics (Komilis, 2020). The most common biomass used for biogas production is:

i. the organic fraction of municipal waste,
ii. the agricultural residues and by products,
iii. the animal manure and slurry,
iv. the digestible organic wastes from food, and
v. the sewage sludge, etc. (Adekunle and Okolie, 2015).

Of particular interest is the production strategy of soil amendment products and biogas through anaerobic digestion of biodegradable MSW at first and then composting of the solid residue, according to relevant research (Preble et al., 2020).

2.6. Primary energy production from municipal solid waste, in EU-27, in 2015 and 2019

In this work, the data regarding the production of primary energy from renewable and non-renewable municipal solid waste for the years 2015 and 2019 were collected for each Member State. Primary energy production from municipal solid waste (MSW) represents the heat produced after combustion (corresponding to the net heating value). As for anaerobic digestion of wet wastes, primary energy production corresponded to the net heating value (heat content) of the biogases generated, including the gases consumed in the installation for the fermentation processes but not of flare (European Commission - Eurostat, 2015). It must be pointed out that renewable was characterized the portion of the municipal waste that was of biological origin (e.g., newspaper, textiles, leather, food wastes, mixed paper, containers and packaging, wood, etc.), while non-renewable the portion of non-biological origin (e.g., plastics, rubber, etc.). These types of wastes were produced by hospitals, the tertiary sector, and households, and incinerated at dedicated installations (EIA, 2007; Commission Regulation 844/2010/EU). Table 4 shows the primary energy production from renewable and non-renewable municipal waste in the EU-27 in 2015 and 2019 and the percentage of change between these years (Eurostat, 2021).

2.7. Gross inland energy consumption by MSW-generated energy

Figure 2 shows the percentages of the gross energy generated from all MSW sources and consumed within each Member State of EU-27 for the years 2015 and 2019 (Eurostat, 2021). According to Eurostat (2021), the gross inland energy consumption is defined as the total energy demand of a country or region, representing the quantity of energy necessary to satisfy inland consumption of the geographical entity under consideration. To obtain the per cent change, the data regarding the gross energy generation from all MSW sources and the percentage of its recovery and consumption were collected and processed by the authors.

Table 4
EU-27: Primary energy production from Renewable and Non-Renewable Municipal Solid Waste, 2015-2019 (Million tons of oil-equivalent)

	2015	2019	% Change 2019/2015
EU-27	16.831	17.987	6.86
Belgium	0.728	0.727	-0.13
Bulgaria	0.015	0.057 (2018)	280 (2015 - 2018)
Czech Republic	0.132	0.151	14.39
Denmark	0.836	0.809	-3.22
Germany	5.988	6.182	3.23
Estonia	0.045	0.042	-6.66
Ireland	0.129 (2016)	0.285 (2018)	120.93 (2016 - 2018)
Greece	0	0	0
Spain	0.504	0.51	1.19
France	2.444	2.51	2.7
Croatia	0	0	0
Italy	1.69	1.746	3.31
Cyprus	0.0005	0.002	300
Latvia	0.006	0.015	150
Lithuania	0.031	0.034	9.67
Luxembourg	0.032	0.037	15.62
Hungary	0.112	0.105	-6.25
Malta	0	0	0
Netherlands	1.436	1.448	0.83
Austria	0.462	0.472	2,16
Poland	0.156	0.487	212.17
Portugal	0.194	0.206	6,18
Romania	0.003	0.004	33.33
Slovenia	0	0	0
Slovakia	0.038	0.056	47.36
Finland	0.471	0.601	27.6
Sweden	1.365	1.485	8.79

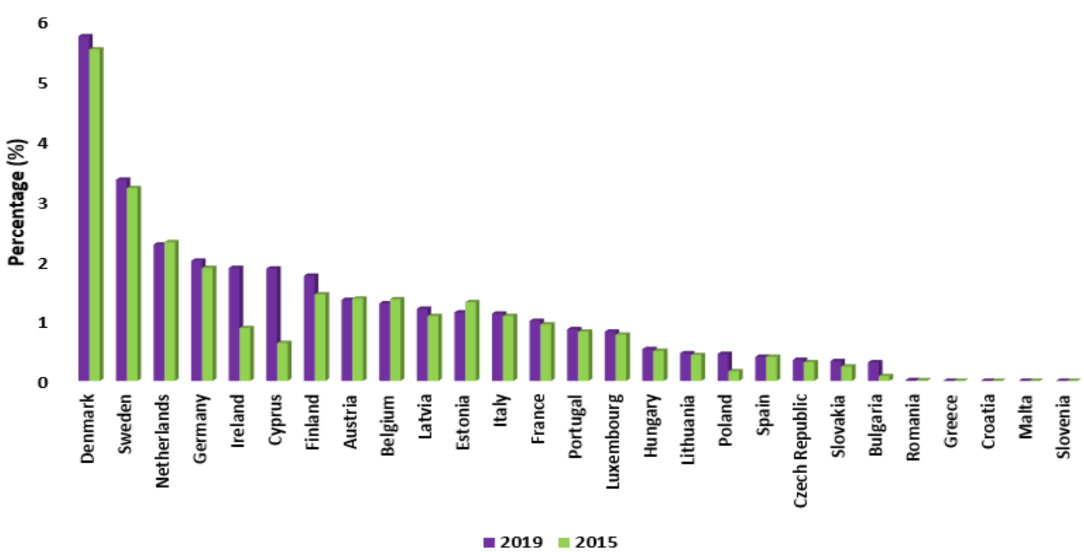

Figure 2. Percentage (%) of energy generated from MSW (renewable and non-renewable) used to cover the gross inland energy consumption in EU-27, in 2019 and 2015

3. Results and Discussion

Table 1 shows that the amount of MSW generated in EU-27 in 2019 was 5.17 % higher than that of 2015. Only in three European countries, the amount of MSW was reduced. These countries were Bulgaria (-4.94 %, comparison period 2015-2018), Germany (-1.96 %), and the Netherlands (-0.67 %). In all other Member States, the increase of this rate was observed. The highest MSW generation in 2019 was observed in Germany (50.62 million tons), followed by France (36.74 Mt), Italy (30.023 Mt), Spain (22.438 Mt), Poland (12.753 Mt), and the other Member States. The highest change, between the generated MSW in 2015 and 2019, was observed in Czech Republic (59.96 %), followed by Luxemburg (41.9 %), Slovakia (28.86 %), Malta (22.8 %), Poland (17.39 %), Finland (14.06 %), Slovenia (13.6 %) and other countries.

Figure 1 shows that the highest change regarding the recovery operations of MSW in EU-27 between 2015 and 2019 was observed in energy recovery (R1) operation (19.7 %), followed by composting and digestion (17.58 %), and recycling (8.62 %). Regarding the percentage of incineration of MSW without energy recovery, it decreased by -86.03 % and the percentage of landfill and other disposal operations decreased by -5.56 %. Based on the aforementioned, it is concluded that the amount of waste subjected to recovery operations increased while the amount of waste subjected to disposal operations decreased. Therefore, it seems that the management of MSW in the European Union is getting improved.

The largest amount of MSW incinerated for energy recovery in 2019 was observed in Germany (15.98 million tons), followed by France (12.461 Mt), Italy (5.711 Mt), the Netherlands (3.577 Mt), Poland (2.742 Mt), Spain (2.533 Mt), Sweden (2.427 Mt), Denmark (2.333 Mt), Belgium (2.021 Mt) and the other countries (Table 2). The highest change between the amount of MSW incinerated for energy recovery in 2019 compared to 2015 was observed in Greece (311.11 %) but with low incinerated quantity, followed by Bulgaria (153.6 %, comparison period 2015-2018), Romania (116.37 %), Poland (108.94 %), Italy (92.35 %), Latvia (86.66 %) and other countries. In some Member States less MSW was incinerated for energy recovery in 2019 compared to 2015. These countries were Slovakia (-34.55 %), Slovenia (-13.92 %), the Netherlands (-11.83 %), Estonia (-9.05 %), Spain (-5.6 %), Denmark (-2.62 %) and Hungary (-1.9 %), as observed in Table 2.

The largest amount of MSW biologically treated (composting and digestion) in 2019 was observed in Germany (9.442 million tons), followed by France (7.394 Mt), Italy (6.387 Mt), Spain (3.751 Mt), the Netherlands (2.569 Mt), Austria (1.677 Mt), Belgium (2.021 Mt) and the other Member States (Table 3). The highest change for the MSW biologically treated in 2019 compared to 2015 was observed in Czech Republic (326.95 %), followed by Slovenia (147.88 %), Croatia (125 %), Lithuania (121.96 %), Greece (109.62 %), Slovakia (106.92 %) and other countries. There were some countries where less municipal solid waste was biologically treated in 2019 compared to 2015. These countries were Bulgaria (-83.27 %), Cyprus (-55.55 %), Romania (-36.52 %), Estonia (-29.41 %), Latvia (-10.63 %), and Sweden (-4.53 %), as observed from Table 3.

In case of Member States with negative incineration (R1) and biological treatment (R3) rates, data were collected and analyzed to investigate whether there was a reduction in quantities leading to disposal operations (D1-D7, D12) and an increase in regards to recycling. As it was observed, there was an increase in recycling rates, between 2015 and 2019, in Slovakia (352.9 %), Latvia (65.9 %), Bulgaria (48.1 %, 2015-2018), Romania (35.2 %), Cyprus (23.1 %), Denmark (21.4 %), Estonia (18.8 %), Spain (12.5 %), the Netherlands (12.1 %), Sweden (5.5 %), Hungary (4.4 %), and Slovenia (3.9 %) and a decrease in disposal operations rates, in Slovakia (-2.9 %), Latvia (-2.4 %), Bulgaria (-12.1 %, 2015-2018), Cyprus (-7.5 %), Denmark (-24.6 %), Spain (-1.73 %), the Netherlands (-0.8 %), Sweden (0 %), Hungary (-3.7 %), and Slovenia (-48.5 %), except Romania (17.1 %) and Estonia (142.8 %) (Eurostat, 2021). According to the aforementioned, the Member States with negative incineration and biological treatment rates increased the amount of waste recycled in 2019 compared to 2015. The same applied to the quantities of waste subjected to disposal operations (D1-D7, D12), except for Estonia and Romania, where the quantity of wastes directed to disposal operations increased by 142.8 % and 17.1 %, respectively. As for Sweden, in case of waste disposal (D1-D7, D12) it seems that the percentage did not change. The purpose of this analysis was to investigate whether the situation improved in other municipal solid waste management processes as there was a reduction in incineration energy recovery rates (Slovakia, Slovenia, the Netherlands, Estonia, Spain, Denmark and Hungary) and in biological treatment rates (Bulgaria, Cyprus, Romania, Estonia, Latvia and Sweden).

Figure 3 shows the percentage of MSW incinerated for energy recovery and the percentage of MSW biologically treated in relation to the total MSW generated in each Member State for the year 2019. In the Nordic countries a great share of the generated MSW was incinerated for energy recovery (R1). In Finland, for example, the share was 55.55 %, in Sweden 52.63 %, and in Denmark 47.54 %. Luxembourg (46.63 %), Estonia (45.1 %), Ireland (42.68 %, 2018), Belgium (42.28 %), the Netherlands (40.62 %), Austria (38.39 %), France (33.91 %), and Germany (31.57 %) also showed high percentages. In most Member States, the share of MSW incinerated with energy recovery (R1) was greater that the corresponding biologically treated (R3). For example, in Poland, a smaller amount of MSW was biologically treated (9.04

%) than incinerated for energy recovery (21.5 %). In nine Member States only, the amount of MSW biologically treated was higher than the incinerated for energy recovery. These countries were Italy, Lithuania, Slovenia, Spain, Slovakia, Latvia, Greece, Cyprus, and Croatia.

An innovative method (Chen et al., 2022), according which anaerobic digestion of organic waste and incineration of municipal solid waste are combined for energy production is interesting. As biogas is recovered through anaerobic digestion, it is collected and used by a gas turbine in order to enhance the steam cycle of the incineration unit with significant financial benefits.

According to Table 4, the largest production of primary energy from renewable and non-renewable municipal waste in 2019 was observed in Germany (6.182 million tons of oil-equivalent). The other countries following were France (2.51 Mtoe), Italy (1.746 Mtoe), Sweden (1.485 Mtoe), the Netherlands (1.448 Mtoe), Denmark (0.809 Mtoe), Belgium (0.727 Mtoe), Finland (0.601 Mtoe), Spain (0.51 Mtoe), etc. Increase in primary energy production from renewable and non-renewable municipal waste between 2015 and 2019 was observed in most Member States except the following four: Estonia (-6.66 %), Hungary (-6.25 %), Denmark (-3.22 %), and Belgium (-0.13 %). It seems that Cyprus (300 %) had the largest increase in primary energy production from renewable and non-renewable municipal waste between 2015 and 2019, being followed by Bulgaria (280 %, comparison period 2015-2018), Poland (212.17 %), Latvia (150 %), Ireland (126.61 %, comparison period 2016-2018), etc. (Table 4).

Table 5 presents the total production of primary energy from all sources and the percentage of primary energy produced from renewable and non-renewable municipal solid waste in the EU-27 in 2015 and 2019 (Eurostat, 2021).

In most Member States, the percentage of primary energy production from renewable and non-renewable municipal solid waste increased in 2019 compared to 2015. Only in six Member States this percentage decreased. These countries were Belgium, Spain, Lithuania, Luxembourg, Hungary, and Portugal. The percentage presented by Luxembourg is impressive, as, according to the data in Table 5, 21.05 % of the total primary energy production in 2015 originated from MSW. Regarding 2019, this percentage was 15.94 %. A large increase of this percentage was observed in Bulgaria (from 0.12 % in 2015 to 0.49 % in 2018), Ireland (from 3.04 % in 2016 to 5.65 % in 2019), Cyprus (from 0.38 in 2015 to 0.96 in 2019), Latvia (from 0.25 % in 2015 to 0.53 % in 2019), The Netherlands (from 2.98 % in 2015 to 4.37 % in 2019), and Poland (from 0.23 % in 2015 to 0.82 % in 2019), as shown in Table 5.

According to the data in Figure 3, it seems that most of the Member States, especially the central and the northern ones (i.e., Germany, France, Nordic countries, etc.), covered between 0.9 and 5.7 % of their gross inland energy consumption by MSW-generated energy.

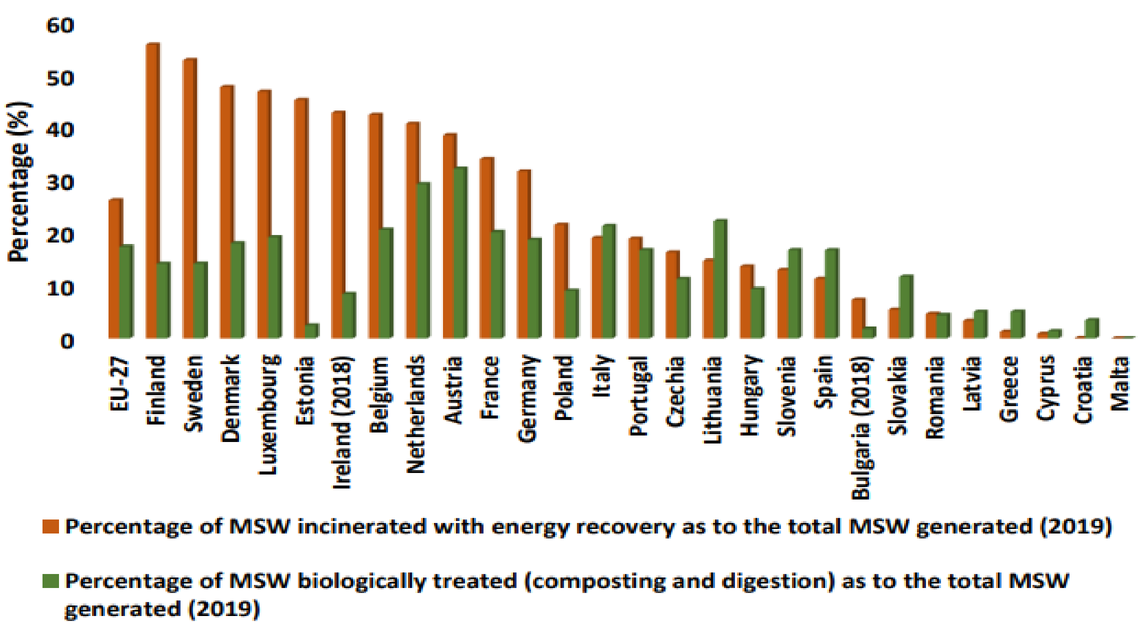

Figure 3. Percentage of MSW incinerated with energy recovery and biologically treated (composting and digestion) in reference to the total MSW generated in EU-27 in 2019

Table 5
Primary energy production from all sources and percentage of primary energy produced from renewable and non-renewable Municipal Solid Waste, EU-27, 2015-2019

	2015*	2015**	2019*	2019**
EU-27	658.334	2.55	615.946	2.92
Belgium	10.818	6.72	15.946 (2018)	4.55
Bulgaria	12.032	0.12	11.957	0.49
Czech Republic	28.553	0.46	26.597	0.56
Denmark	16.239	5.14	12.509	6.46
Germany	120.545	4.96	105.426	5.86
Estonia	5.591	0.8	4.909	0.85
Ireland	4.237 (2016)	3.04 (2016)	5.037 (2018)	5.65 (2018)
Greece	8.529	0	6.367	0
Spain	34.013	1.48	34.981	1.45
France	140.81	1.73	133.92	1.87
Croatia	4.414	0	3.9	0
Italy	36.098	4.68	36.909	4.73
Cyprus	0.13	0.38	0.208	0.96
Latvia	2.338	0.25	2.826	0.53
Lithuania	1.859	1.71	2.039	1.66
Luxembourg	0.152	21.05	0.232	15.94
Hungary	11.104	1	10.785	0.97
Malta	0.0156	0	0.38	0
Netherlands	48.107	2.98	33.116	4.37
Austria	12.228	3.77	12.359	3.81
Poland	67.759	0.23	59.345	0.82
Portugal	5.907	3.28	6.561	3.13
Romania	26.374	0.011	24.529	0.016
Slovenia	3.317	0	3.378	0
Slovakia	6.394	0.59	6.939	0.8
Finland	17.213	2.73	19.268	3.11
Sweden	35.821	3.81	37.019	4.01

* Total Primary energy produced from all sources (Million tons of oil- equivalent)
** Primary energy produced from renewable and non-renewable MSW (%)

4. Conclusions

In order to determine the importance of municipal solid waste used in energy production through incineration (R1) and biological treatment (R3), out of total solid waste utilized for energy recovery, data on the total solid waste used for energy recovery in 2016 and 2018 were collected to be used with the findings of the present work. These years have been selected as reference years, because of lack of statistics on the total solid waste used for energy recovery in 2015 and 2019 from Eurostat database. According to this database, 120.85 million tons of solid waste was used for energy recovery in 2016 (Eurostat, 2021). As for 2018, the quantity was 129.72 Mt (increase by 7.3 %). According to the findings of the present analysis, the aggregate of municipal solid waste subjected to incineration (R1) and biological treatment (R3), in 2015 and 2019, were 82.094 and 97.566 million tons, respectively (increase by 18.8 %). Based on data between 2015 (MSW incinerated R1 and biologically treated R3) and 2016 (total solid waste for energy recovery), as well as the corresponding between 2018 and 2019, it was concluded that the percentage of MSW for energy recovery increased from 67.9% in 2016 to 75.21 in 2018. As the data from different years were used (2015/2016 and 2018/2019), it must be pointed out that the percentage was approximate. The specific purpose of that reference is to point out the important role of municipal solid wastes and their contribution to the energy recovery from waste in the EU-27 in reference to the total solid waste.

Also, in the case of primary energy production from municipal solid waste, it was necessary to cite data from previous years (2010 and 2018) in combination with the findings of the present work in order to justify the increasing trend of primary energy production from MSW. Primary energy supply from municipal solid waste (renewable and non-renewable) followed an ascending trend. Primary energy production from MSW in 2010 was 14.496 million tons of oil-equivalent (Mtoe) (Eurostat, 2021), 16.831 Mtoe in 2015 (Table 4), 17.742 Mtoe in 2018 (Eurostat, 2021), and 17.987 Mtoe in 2019 (Table 4). The percentage of primary energy production from MSW in relation to the total primary energy production from all sources for the years 2010, 2015, 2018, and 2019 was 2.08 %, 2.55 % (Table 4), 2.79 %, and 2.92 % (Table 4), respectively. According to these specific percentages, it seems that the production of primary energy from renewable and non-renewable municipal solid waste in the EU-27 increased over the years.

Combining the f indings of this study, it is concluded that Germany and France were highly active in Waste-to-Energy, as the number of existing plants in these two countries exceeded the sum of the rest. Therefore, a large amount of MSW was utilized for energy recovery. There was also an important activity in the sector of waste-to-energy in the Nordic countries (Sweden, Denmark, and Finland), as well as in Italy, Belgium, Austria, the Netherlands, Poland, and Spain. In countries such as Slovakia, Slovenia, Greece, Latvia, Cyprus, Croatia, and Malta, more effort was required to achieve higher level of Waste-to-Energy, without affecting the increase in quantities leading to other more environmental-friendly waste management operations (prevention, reuse and recycle) which were of major priority.

In general, there were no significant differences in the rate of gross inland energy consumption by MSW-generated energy in the four-year period (2015-2019) in the Member States. A relatively small increase in this percentage was observed in Ireland, Cyprus, and Poland, as observed in Figure 2.

Although in some Member States (i.e., Hungary, Spain, Bulgaria, The Netherlands, etc.) there was a decrease in the quantities of waste incinerated for energy recovery (R1) and subjected to biological treatment (R3), increasing rates in recycling and decreasing rates in disposal operations were observed, which denoted improvement of waste management in these countries, despite the declining rates of energy recovery operations.

In terms of the overall municipal solid waste management, and especially incineration (R1) and biological treatment (R3) with which the current paper deals, it seems that the situation improved, despite the significant differences between the Member States. Circular Economy can play an essential role to meet the goals towards climate neutrality in Europe, as all Member States will keep going on and increasing their efforts in this respect.

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Pretvaranje komunalnog čvrstog otpada u energiju u EU-27 kao korak ka kružnoj ekonomiji

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WtE tehnologije

I Z V O D

Ovaj rad se bavi obnavljanjem energije iz čvrstog komunalnog otpada putem spaljivanja (R1) i biloškog tretmana (R3) u okviru EU-27 kao koraku ka kružnoj ekonomiji. Zakonodavstvo EU je analizirano u odnosu na proizvodnju i upravljanje komunalnim otpadom za dobijanje energije, zajedno sa procesima pretvaranja otpada u energiju (spaljivanje, anaerobna digestija i kompostiranje, piroliza, gasifikacija, plazma tehnologija i deponijski gas). Kao referentne godine uzete su 2015. i 2019. godina, koje predstavljaju prvu godinu predstavljanja evropskog plana za kružnu ekonomiju (COM-(2015)-614) i godinu pre predstavljanja COM-(2020)-98. Takođe su prikupljeni i obrađeni podaci svake države članice za 2015. i 2019. godinu, koji obuhvataju ukupno proizvedeni komunalni otpad, ukupan komunalni otpad koji se koristi za dobijanje energije spaljivanjem i biološkim tretmanom, proizvodnaj primarne energije iz obnovljivih i neobnovljivih komunalnih otpadnih voda, kao i bruto domaća potrošnja energije dobijene od komunalnog otpada. Glavni zaključak koji je donesen na osnovu ovog rada bio je trend porasta količine komunalnog otpada koji se koristi za dobijanje energije u EU-27, kao i trend povećanja proizvodnje primarne energije iz komunalnog otpada koji je EU posmatrala kao agregat. Uočeno je da je u nekim državama članicama energija pratila trend rasta sa većom ili nižom stopom, dok je kod drugih imala opadajući trend. Uprkos opštem trendu povećanja proizvodnje energije iz komunalnog otpada, stopa je još uvek relativno niska kod nekih zemalja i potrebno je uložiti veći napor kako bi se uskladila sa politikom EU na putu ka kružnoj ekonomiji.

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Decision making tools in regional sanitary landfill location selection

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ABSTRACT

The paper applies intelligent multicriteria analysis in order to rank the criteria in the process of site selection for the Regional Sanitary Landfill. The analysis was performed for 3 pre-selected sites that were selected based on available area, site access, potential preparation difficulties, groundwater occurrence, biodiversity, and proximity to urban area. These locations were selected as the most suitable for construction, both from the engineering and from the economic and environmental aspect. The analysis is the best example of the application of intelligent multicriteria analysis as a useful tool for environmental management in the decision-making process. The analysis was performed for three proposed locations of the Regional Sanitary Landfill: Kasilo, Kristal, and Savina Stena, in the municipalities of Zvecan and Leposavic. In order to achieve the most objective results, PROMETHEE methods were applied. Using these calculation methods, the following ranking list of locations for the Regional Sanitary Landfill was obtained according to their suitability: Savina Stena, Kasilo, and Kristal. This result can contribute to the decision-making process of determining the development strategy at the local and regional level.

1. Introduction

The adoption of new legislation related to the treatment of municipal waste, with the aim of reducing its generation and disposal and to minimize its harmful impact on the environment, has intensified in the last decade. However, waste disposal at sanitary landfills is still the most common final solution. The purpose of the landfill was to protect the environment and in that respect, it brought certain solutions, but it also opened other, new problems, such as the creation of gas, wastewater, noise, fire, etc. (Zamorano et al., 2005). The leading problems related to the environment and sanitary landfills are leachate, fires, and gas generation. Considering the consequences for the environment, maximum efforts are made and new, modern solutions are found, in order to avoid any negative impact. Stopping the degradation of the environment and improper disposal of municipal waste is supported by laws and regulations on measures that must be followed when building landfills and determining their location. The rules refer to the distance of landfills from settlements, parks, sports fields, rivers, agricultural goods, etc., however, additional efforts are needed to protect the air, land, groundwater and surface water. Complex problems require great effort, work, commitment and introduction of innovations in the planning and design of sanitary landfills.

Waste management is a complex, responsible, and necessary business, encompassing environmental, social, technological, legal, economic, and cultural aspects. Pursuant to the Law on Waste Management, all activities

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are carried out in a way that provides the lowest risk to endangering the life and health of people and the environment, control and reduction measures:

- Water, air, and soil pollution,
- dangers to flora and fauna,
- dangers of accidents,
- explosions or fires,
- noise levels and unpleasant odors (Official Gazette of the RS, no. 36/2009, 88/2010, 14/2016 and 95/2018).

Even if they are relatively rare, landfill fires are extremely harmful because they emit various pollutants into the air, water, and soil. Landfill fires differ in the place of origin, in the materials that catch fire, the cause of the occurrence, etc., but they are all, without exception, a challenge to bring under control and extinguish (FEMA, 2002).

By penetrating into the interior of the soil or moving through channels and cracks, leachate migrates from the body of the landfill to surface and groundwater and pollutes them. In addition to water, only the soil through which the filtrate passes is contaminated.

Noise from communal landfills can have an extremely negative impact on people, depending on the health profile of the inhabitants of the surrounding settlements. Noise emitters from landfills are transport vehicles, excavators, waste compactors, etc. In the EU, as many as 4% of the population has a permanent hearing problem, due to frequent exposure to noise (Belić et al., 2009). As a product of microbiological decomposition of waste in landfills, intense unpleasant odors are created that significantly affect the quality of life of the local population. The intensity and frequency of unpleasant odors depend on a number of microclimatic factors (Šobot-Pešić et al., 2016).

1.1. Modern methods for selection of suitable location for landfill

In the complex process of waste management, choosing a location for the construction of a municipal landfill is a burning issue. Using the development of science and modern technologies, a multitude of methods for landfill site selection have been developed.

Modern methods, which have enabled us to develop informatics and computing, have an invaluable role in the entire waste management process. Through various software programs that can be used for analysis, calculations, simulations, etc., the speed and accuracy of work has increased. When choosing a site for a sanitary landfill, modern methods such as: GIS, MCDA methods, PROMETHEE, Heuristic approach, logical methods, MCDM obscure methods, etc., have an advantage over earlier methods based on mathematical calculations or manual techniques, such as technique coatings (Mokhtarian et al., 2014).

Geographic information systems, GIS, is a tool that allows you to select the best location and to create maps of exceptional quality (Ajibade et al., 2019). With the improvement of GIS, the possibility of screening, zoning, correlation, data storage, and graphical display of sites was achieved (Shah and Wani, 2014; Dereli and Trecan, 2021). GIS enables data management and combination with other methods (Mohammed et al., 2017). The application of GIS tools, alone or in combination with appropriate methods of analysis, offers solutions to structural problems encountered in the process of finding a suitable site for a landfill (Demesouka et al., 2014). In practice, it is most often combined with MCDA, which results in time saving and cost reduction (Mat et al., 2017; Eghtesadifard et al., 2020). GIS and MCDM methods in combined application define optimal areas, while for precise determination of landfill location subjective weighting method, sum of titles (RS), mutual rank (RR), and order of ranks (ROC) methods are used (Dereli and Tercan, 2021). Looking at the problem as an element or network of decision-making elements enables the analytical network process (ANP), which is basically a generalized AHP (Eghtesadifard et al., 2020). Flexibility in the work of ANP and AHP, enables their application for all sites and declares them as extremely suitable for combination with other methods of analysis in the process of landfill site selection (Afzali et al., 2014). The process of analytical hierarchy (AHP) is a method whose application provides a clear ranking of the final solutions for the landfill location (Mat et al., 2017). In the hierarchy-based AHP method, the Saaty scale is used to evaluate the problem. The Saaty scale is used to classify elements from the same hierarchical level based on importance (Srđević and Srđević, 2004; Lakićević et al., 2017).

SAV (simple additive weighting) is often referred to in the literature as a "scoring method" and is used in the processing of spatial attributes (Mat et al., 2017). The SAV format can be both raster and vector (Mohammed et al., 2017).

The fuzzy AHP method is applied to eliminate inaccuracies, while the integrated fuzzy VIKOR technique highlights priority in the event of conflicting decision-making criteria. The integrated obscure TOPSIS technique contributes to finding the optimal solution for the landfill site, while the integrated obscure ANP method is used to analyze the suitability of the site in an unclear environment. The heuristic approach is a two-phase method, where the first phase selects a significant area for the landfill, while the second specifies the location of the landfill, within the selected area. PROMETHEE is an extremely efficient technique that provides a final and complete ranking of selected locations, from the most to the least desirable (Mat et al., 2017). The Algorithm K method allows clustering, while methods such as MOORA, VASPAS, and KORPAS are used to define locations based on priorities (Eghtesadifard et al., 2020).

For precise standardization of the established criteria, the FUZZI LOGIC method is applied, while the Regulated Weighted Average (OVA) is a newer technique that achieves top results in site planning (Mohammed et al., 2017). VLC (weighted linear combination) is a method used to select the right one from several offered alternatives (Dareli and Tercan, 2021). FUZZI MADM method, unclear AHP method, and Chang's FUZZI AHP method, are often combined, whereby FUZZI MADM in solving problems arising from obscure, subjective and imprecise information, unclear AHP for selection and ranking of obscure programs in simple, while Chang's FUZZI AHP method is necessary in ranking alternatives (Nazari et al., 2012). Apart from the mentioned modern methods, the following are also significantly applied: weighted linear combination (VLC), unclear analytical hierarchical procedure (F-AHP), unclear analytical network process (F-ANP), TODIM, unclear TODIM, gray systems theory, etc. (Rezaeisabzevar et al., 2020).

1.2. Application of modern methods

Choosing a site suitability analysis method is a complex process, depending on many factors. Goulart Coelho et al. (2017) also emphasized the complexity of deciding on the selection of the appropriate multicriteria technique for the selection of the location of the communal landfill, and the analysis of 260 papers dealing with this topic, confirmed that the selection of tools was an extremely sensitive task, but that their application raised the choice of location for the landfill from the bottom to the top of the priority scale.

In Morocco in the Beni Mellal-Khouribga region, using GIS, Boolean logic, and the AHP method, the obtained results show that only 10 % of the land designated as an alternative for the construction of a municipal landfill is highly suitable for this purpose (Barakat et al., 2017). For the Babylon Governorate in Iraq, 10 sites were identified in 5 districts that were responsible for building the landfill, using GIS, AHP, and RSV methods (Chabuk et al., 2019). Ouma et al. (2011) presented the results of GIS analysis, multi-criteria analysis, and overlay analysis, based on which they determined the optimal location for the municipal waste landfill in the city of Eldoret in Kenya. In the southwest of Colombia, a suitable location has been determined for the construction of a communal landfill, using AHP and TOPSIS techniques (Manyoma-Velásquez et al., 2020). Elahi and Samadyar (2014), by a combination of GIS and AHP methods, established suitable sites for a municipal landfill in the city of Tafresh in Iran. The complex analysis resulted in the selection of three appropriate locations and contributed to the city planning process. Nas et al. (2010) using GIS and multicriteria analysis, identified three potential municipal landfill sites for the city of Konya in Turkey.

1.3. Criteria

The basic criteria for determining the location for a sanitary landfill are grouped into three groups:

- social,
- environmentally friendly, and
- techno-operative.

By applying GIS tools in the area where it is necessary to build a sanitary landfill, favorable and unfavorable location areas are singled out, and this is the basic step in the process of determining the most suitable location for the landfill. Elimination criteria in this case are legal regulations and terrain characteristics, such as slope, altitude, soil composition, etc. This way, the number of localities is reduced to a smaller number of potentially suitable ones. Table 1 shows the number of restrictive criteria which is usually from 20 to 40 (Josimović et al., 2011).

Table 1
Restrictive criteria

1.	Hydrogeology	11.	Underground waters
2.	Distance from the boundary zone of the water source	12.	Distance of surface waters
3.	Distance from the settlement	13.	Air temperature
4.	Location acceptability	14.	Precipitation
5.	Landscape characteristics	15.	Geological characteristics
6.	Distance from roads and railways	16.	Relief
7.	Distance from the natural good	17.	Land use
8.	Distance from cultural monuments	18.	Air flow
9.	Existing infrastructure	19.	Water supply
10.	Landscaping	20.	Seismicity

1.4. Examined locations

The regional landfill will serve the municipalities of Leposavic, Mitrovica (north), Zvecan, and Zubin Potok. Municipalities in northern Kosovo have proposed three (3) new landfill sites, for which they have prepared a comparative report. The construction of a new landfill is urgent in the project region in order to protect human life and the environment. Municipalities in the field of research have had the initiative to look for new locations to accommodate the new sanitary landfill. Representatives of the municipalities of Mitrovica, Zvecan, and Leposavic submitted a plan for the implementation of a new landfill in the area, which included an analysis of various elements for potential locations, i.e., land, groundwater, etc. The final result of the fieldwork was a report presenting 3 potential locations, two of which are located in the municipality of Leposavic and one in the municipality of Zvecan:

1. Location Kristal, industrial landfill, Popovacko Polje,
2. Location Kasilo, on the regional road Leposavic - Kursumlija, and
3. Location Savina Stena, on the main road Raska - Mitrovica.

2. Materials and methods

One of the advantages of MCA is its ability to help a researcher overcome doubts and problems in a consistent manner. Complexity of data in MCA is reflected in the large amount of data, different measuring units of some parameters, and different scales used to analyze the problem. These methods do not replace the decision-making process, but can contribute to understanding the deliberated multi-criteria problem (Agarski, 2014; Milentijević at al., 2016). The criteria selection for assessment is an important and very complex step, determining the final results of the MCA.

In order to ascertain the ranking of potential landfill locations PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation) is used in this paper. The consideration and description of these method from a mathematical aspect is presented briefly considering that these methods are explained in detail in numerous papers (Milentijević at al., 2016).

The PROMETHEE method is one of the most important in the field of multicriteria analysis. This method finds its application in different industrial sectors (mining, chemistry, ecology, medicine, etc.). It allows complete ranking of the alternatives. The method was developed by Jean-Pierre Brans in two basic versions: PROMETHEE I, a method for partial ranking of the alternatives; and PROMETHEE II, a method for complete or combined ranking of alternatives (Albadvi et al., 2007; Milentijević at al., 2016). The most important advantages of this method are its simplicity and that used parameters have an explanation and meaning (Brans, 1982). This method relies on qualitative and quantitative data for each criterion and alternative. The PROMETHEE method introduces preference function *P*(*a*,*b*) for alternatives, a and b, which are valued by function criterion. Alternative *a* is better than *b* according to criterion f if $f\ (a)\ <\ f\ (b)$ (Albadvi et al., 2007; Milentijević at al., 2016). The value of the preference function is within the interval [0, 1], i.e., higher preference is presented by higher function value and vice versa.

The preference function is defined as:

$$P\ (a,b)\ = \begin{cases} 0, if d \leq 0 \\ 1, if d\ > 0 \end{cases} \quad (1)$$

In this case, the following combinations of the function of preference are possible:

- P(a,b) = 0 no preference, indifference,
- P(a,b) ≅ 0 weak preference, k (a) >k (b),
- P(a,b) ≅ 1 strong preference, k (a) >>k (b),
- P(a,b) = 1 tough preference, k (a) >>> k (b).

After that it can be concluded that there are the following two features of the preference function:

$$\begin{array}{l} 0\ \leq\ P(a,b)\ \leq\ 1, \\ P(a,b)\ \neq\ P(b,a) \end{array} \quad (2)$$

The basic precondition of the functioning of PROMETHEE is to define the general set of criteria for each individual criterion $k\ (a)$. There are six types of the general criteria. In creation of the specific model for each type of general criterion, the parameters must be determined. In the next section, the presentations of each individual parameter are given. For the shorter text, the sign d is involved, $d\ =\ f\ (a) - f\ (b)$. According to Brans and Mareschal (1984), and Milentijević at al. (2016), there are six types of preference function:

I “Simple” criterion

$$P\ (a,b) = \begin{cases} 0, if d \leq q \\ 1, if d\ > q \end{cases} \quad (3)$$

II Quasi criterion

$$P\ (a,b) =\ \begin{cases} 0, if d \leq 0 \\ 1, if d\ > q \end{cases} \quad (4)$$

III Criteria for linear preference

$$P(a,b) = \begin{cases} 0, if\ d \leq 0 \\ d/p\ , if\ 0 < d \leq p \\ 1, if\ d > p \end{cases} \quad (5)$$

IV Nivoj criterion-stage criterion

$$P(a,b) = \begin{cases} 0, if\ d \leq 0 \\ 1/2\ , if\ 0 < d \leq p \\ 1, if\ d > p \end{cases} \quad (6)$$

V Criterion with linear preference and domain of indifference

$$P(a,b) = \begin{cases} 0, if\ d \leq 0 \\ \dfrac{d-p}{p-q}, if\ 0 < d \leq p \\ 1, if\ d > p \end{cases} \quad (7)$$

VI Gauss criterion

$$P(a,b) = \begin{cases} 0, if \ldots d \leq 0 \\ 1 - e^{\frac{d^2}{21f^2}} if \ldots d > q \end{cases} \quad (8)$$

For the multi-criteria analysis method, PROMETHEE involves preference streams: positive stream and negative stream.

The higher + than the other alternatives, however, means further domination over another alternative in the system of alternatives. As a measure for multi-criteria evaluation, the PROMETHEE II involves absolute flow:

$$\phi_j(a_j) = \phi_j^+(a_j) - \phi_j^-(a_j): j = 1, \ldots, J \quad (9)$$

where J is the number of alternatives (Milentijević at al., 2016).

In the analysis conducted in this paper for the PROMETHEE method, the commercial software Visual PROMETHEE 1.4 Academic Edition (http://www.promethee-gaia.net) was used. The PROMETHEE method does not provide the opportunity to analyze decision making on simpler parts. In cases of a bigger number of criteria, this method makes it harder to come to a conclusion for the analyzed problem (Macharis et al., 2004; Milentijević at al., 2016). For a more complete graphic presentation of the results obtained by the PROMETHEE method, the GAIA plan (Geometrical Analysis for Interactive Assistance) was used from the software Visual PROMETHEE 1.4 Academic Edition. The basic purpose of this application is better visual presentation of the multi-criteria analysis. In the frame of the GAIA plan, some information can be lost after the projection. Based on the main components, the presentation is defined by two vectors, responding to the basic flow of one criterion. Although GAIA includes some percentage of total information, it does not provide strong graphic support (Đokić at al., 2020).

3. Results and Discussion

Municipalities in the field of research had the initiative to look for new locations to house the new sanitary landfill. Representatives of three municipalities, Mitrovica, Zvecan, and Leposavic, formed a commission whose task was to submit a plan for the implementation of a new landfill in the area, to determine the potential location of the new landfill, to analyze various elements for potential locations, i.e. land, groundwater size, etc. The Commission prepared a report in which 3 potential locations were introduced, two of which are located in the municipality of Leposavic and one in the municipality of Zvecan:

1. Location Kristal, industrial landfill - Popovacko Polje,
2. Location - Kasilo - on the regional road Leposavic - Kursumlija, and
3. Location, near the village of Srbovac called Savina Stena - on the main road Raska - Mitrovica.

3.1. Site No1 - Location Kristal

- Land use: The location is not included in any strategic or planning documents for the Leposavic municipality. The estimated volume of the site is: V = 21.218,25 m^3.
- Due to the previous use of the ground striking bays and concrete dam have been created. Ownership: Trepca, public enterprise Srbija Sume and socially owned enterprise Farmers' Cooperative.
- Distance from the inhabited location is 3.35 km.
- Configuration of the site is satisfactory.
- Road access to the site is satisfactory.
- Capacity of the site is not satisfactory.

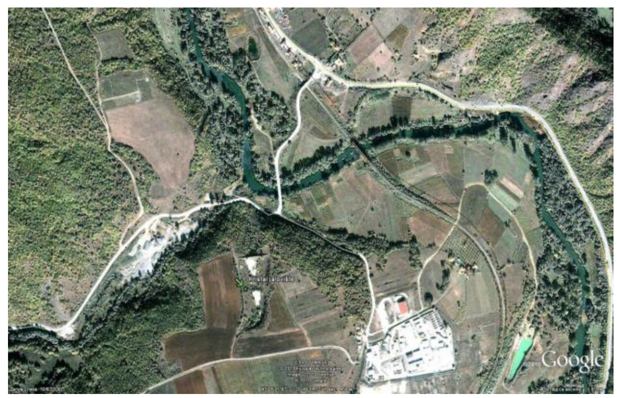


Figure 1. Location Kristal

3.2. Site No2 - Location Kasilo

- Land use: The location is not included in any strategic or planning documents for the Leposavic municipality.
- The estimated volume of the site is: V = 50.000 m^3 from which 10.500 m^3 for the 1st phase of operation and 30.500 m^3 for the 2nd phase of operation.
- Ownership: Private owners.
- Distance from the inhabited location is 3.15 km.
- Configuration of the site is satisfactory.
- Road access to the site is satisfactory.
- Capacity of the site is satisfactory.

From an existing project documentation the following elements were derived: a) wind orientation is northeast-southwest, the location is not much exposed to wind; due to the hydrology purposes the, regulation of the Kasilo stream will be necessary, as well as detailed analysis of the local springs and their possible contamination by the landfill.

Figure 2. Location Kasilo

3.3. Site No3 - Location Savina Stena

- Land use: The location is not included in any strategic or planning documents for the Zvecan municipality.
- The site is located above the river Ibar.
- The estimated volume of the site is V= 35.000 m³.
- Ownership: Public land.
- Distance from the inhabited location (Srbovac) is 1.5 km.
- Configuration of the site is satisfactory.
- There is no access to the proposed site, therefore new access road should be constructed. The ownership of the land for the access road is private.
- Capacity of the site is satisfactory.

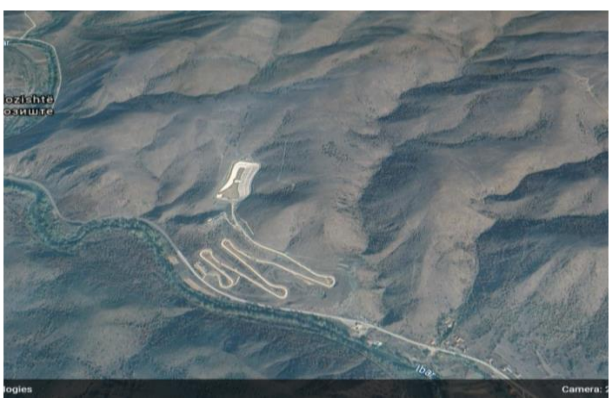


Figure 3. Location Savina Stena

Comparing the influence of certain criteria to the environment was based on relevant data obtained in the field. In Table 2, analyzed criteria, which were used as input data for matrix formatting and quantification for coupled comparison of criteria, are shown. Those data were than included into the calculations by PROMETHEE method, by common steps in calculation process (Milentijević at al., 2016).

Alternatives were evaluated and a quantified matrix of decision making was formed (Table 3) by application of the PROMETHEE method for evaluation of environmental influence of tailing ponds. In this process, certain criteria had a quantitative structure, while others were qualitative. Consequently, certain criteria (C1, C2, C3, C4, C5, C8, and C9) were stated quantitatively, while others were stated qualitatively. The application of qualitative and quantitative scales provided confidence that all criteria were well arranged in the best manner possible (Milentijević at al., 2016).

Table 2
Presentation of criteria of analyzed landfill sites

Criteria	Analyzed Criteria
C1	Proximity of the settlement
C2	Proximity of permanent water flow
C3	Geological environment
C4	Ownership
C5	Volume/ Capacity
C6	Distance from users
C7	Public acceptance
C8	Existence of the flooding water sources
C9	Proximity of the Agricultural area

After quantified matrix of decision making was provided, analyzed alternatives (tailing ponds) were evaluated using Visual PROMETHEE software. This resulted with a rank order of alternatives. Multi-criteria ranking method PROMETHEE introduced qualities of positive, negative, and net flow. The results obtained from positive, negative, and net flow are presented in Table 4 and Table 5 (Milentijević at al., 2016).

Table 4
PROMETHEE positive and negative flows

Alternatives	Ph+	Ph−
Savina Stena	0.4758	0.3808
Kasilo	0.4758	0.4525
Kristal	0.4050	0.5234

Table 5
PROMETHEE NET flow

Alternatives	Net flow Ph
Savina Stena	0.0950
Kasilo	0.0234
Kristal	-0.1184

The ranking was arranged in descending order of net flow value. The best proposal was the one having the highest net flow value, that is, the Savina Stena alternative.

The ranking of the analyzed alternatives is given in Figures 4-6 using the PROMETHEE method.

In Figure 4, the final ranking of analyzed tailing ponds is given. This figure is based on net flow Phi. The upper half of the given scale (colored in green) represents positive Phi value, and the lower half (red) represents negative Phi value. Alternative Savina Stena was at the top of the analyzed alternatives, preceding Kasilo, and

Kristal. Values of the Phi flow for these alternatives are given in Figure 5 (Milentijević at al., 2016).

Figure 5 shows a diamond PROMETHEE solution.

This solution shows partial PROMETHEE I and final ranking PROMETHEE II in a two-dimensional model (Đokić at al., 2020).

Table 3
Quantified matrix of decision making (Evaluation matrix)

SCENARIO 1	Proximity of the settlement	Proximity of permanent water flow	Geological environment	Ownership	Volume/ Capacity	Distance from users	Public acceptance	Existence of the flooding water sources	Proximity of the Agricultural area
Unit	m	m	unit	unit	m³	km	unit	unit	m
Cluster/group		◊	◊	□	□	◊	◊	◊	◊
Preferences									
Min/max	max	max	max	max	max	min	max	min	max
Weight	14.33	9.5	9.5	14.33	9.5	9.5	14.33	9.5	9.5
Preference Fn.	U-shape	usual	usual	usual	usual	usual	level	usual	usual
Tresholds	absolute	absolute	absolute	absolute	absolute	absolute	percentage	absolute	absolute
Q: Indfference	1	n/a	n/a	n/a	n/a	n/a	1	n/a	n/a
P: Preference	n/a	n/a	n/a	n/a	n/a	n/a	2	n/a	n/a
S: Gaussian	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Statistics									
Minimum	1500	301	0.2	0.1	21285	13.75	0.1	0	100
Maximum	3350	2758	0.5	1	50000	31.5	1	0.8	1000
Average	2666.67	1519.67	0.33	0.53	33761.67	21.42	0.7	0.3	433.33
Standard Dev.	828.99	1003.16	0.12	0.37	12020.83	7.45	0.42	0.36	402.77
Evaluations									
Kristal	3350	301	0.5	average	bad	19	1	0.5	200
Savina Stena	1500	1500	0.2	very good	good	13.75	1	0.1	1000
Kasilo	3150	2758	0.3	good	very good	31.5	0.3	0	100

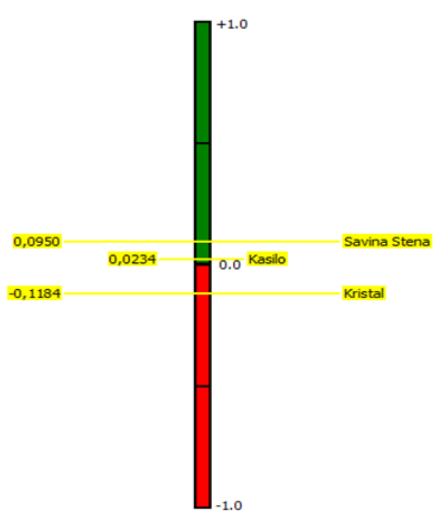


Figure 4. Final ranking

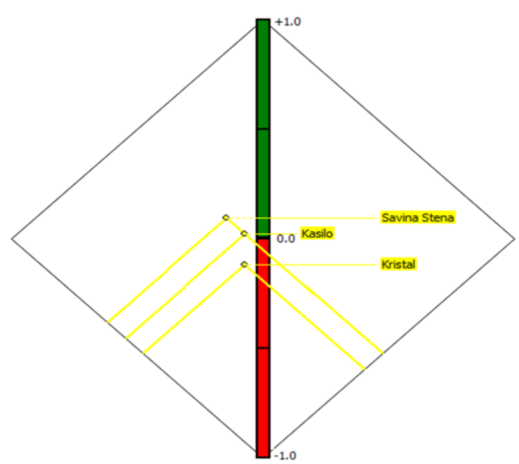


Figure 5. PROMETHEE diamond solutions

The PROMETHEE diamond solution was presented with the dot on (Phi+, Phi−) flat. The flat was at an angle of 45° so that the vertical dimension (red-green axis) corresponded to Phi net flow. A cone was drawn for every alternative (Milentijević at al., 2016). The highest priority alternative was Savina Stena, and the lowest was alternative Kristal.

In Figure 6, the GAIA plan is shown (Geometrical Analysis for Interactive Assistance), which is a descriptive addition to the PROMETHEE ranking. Every alternative was presented with a dot found on the GAIA plan. The position of these alternatives was connected with the marks of a set of criteria. Each criterion was presented with the axis from the center of the GAIA plan. The orientation of these axes showed how these criteria were interrelated. The determination axis (red axis) suggested the alternative tailing Kristal had the least favorable impact on the surrounding ecosystem (Milentijević at al., 2016).

The performance profiles shown in Figure 7 show a special view of the strengths and weaknesses of the alternatives based on the inserted criteria values. Action profiles are a graphical representation of the net flow results for the criteria. For each alternative, upward is interpreted as a positive result, while downward bands are interpreted negatively. For example, for the Savina Stena alternative, only the criteria Proximity of the settlement and Geological environment had negative results.

The results of the comparison are affected by the weights assigned to the criteria, so it is important to know how the ranking changes when the weights change. A special feature of the software called walking weights allows the sensitivity analysis of the final results, when the weights change. The Walking Weights feature allows you to increase the weight of a certain criterion while reducing the weight of other criteria proportionally. Variations were observed, but there were no changes in the order of alternatives. When the criteria gained equal weight, the sensitivity analysis showed that the ranking of alternatives was quite stable, i.e. that there was no change in the final ranking (Figure 8). Savina Stena's alternative was still the best choice. It is clear from this analysis that the weights of the criteria do not affect the final ranking.

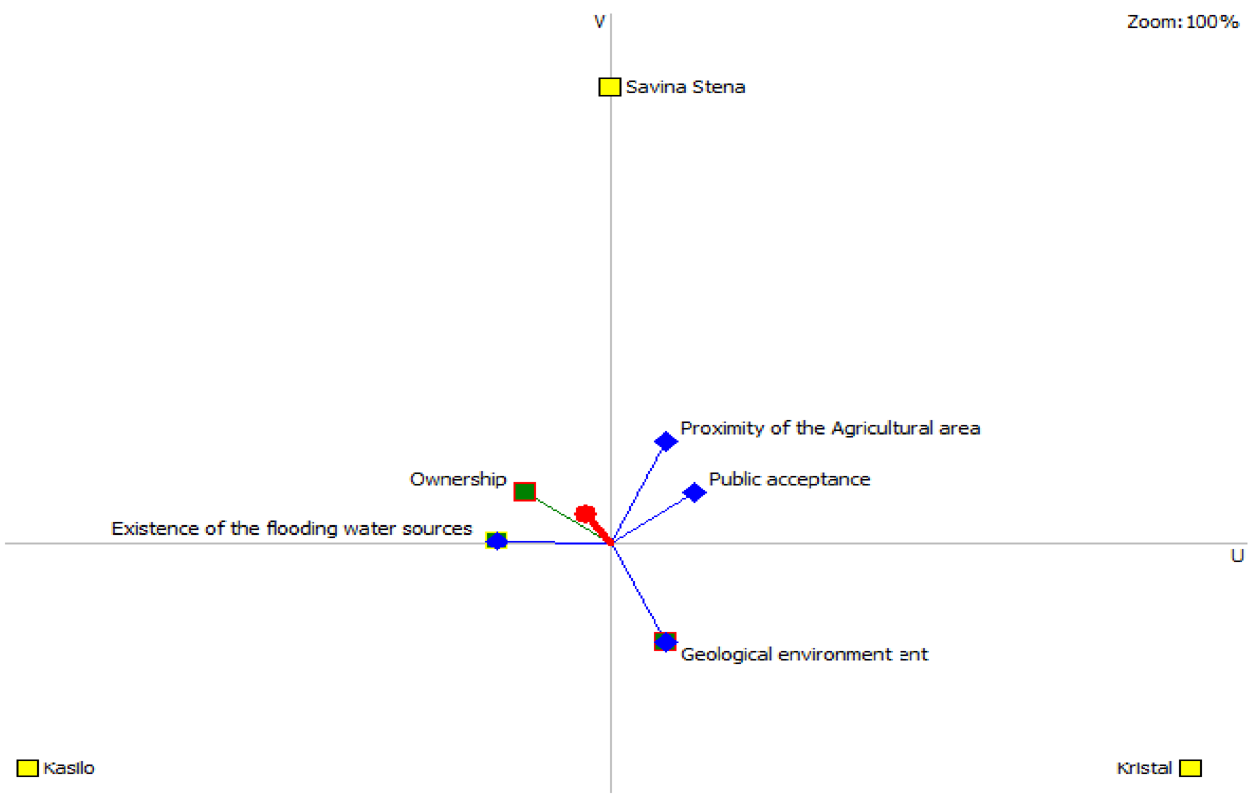


Figure 6. GAIA plan for landfill location

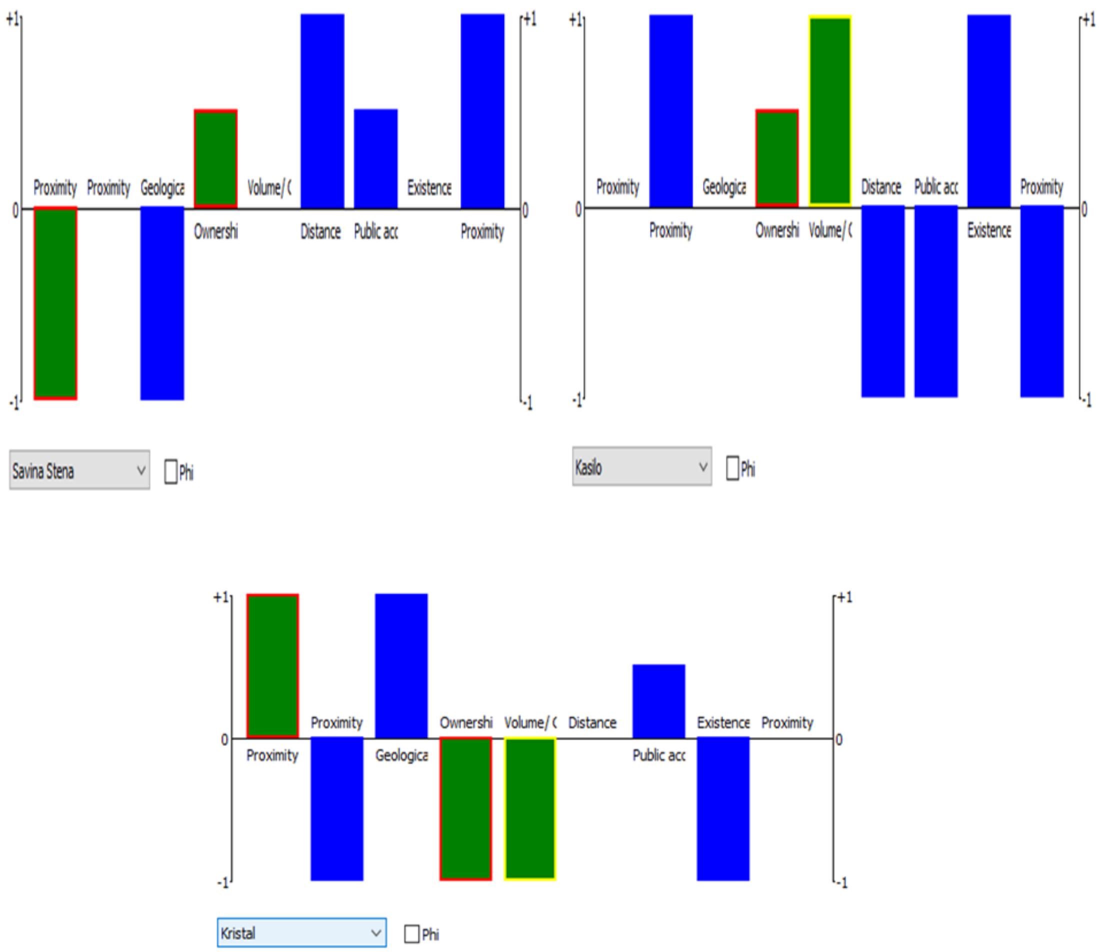
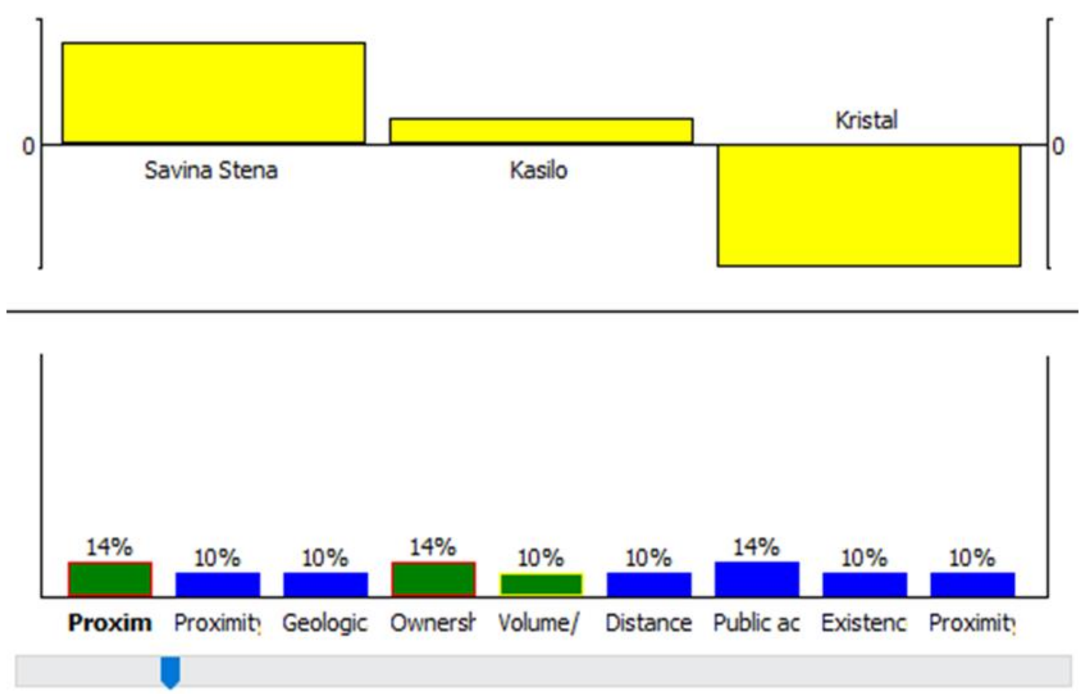


Figure 7. Action profile



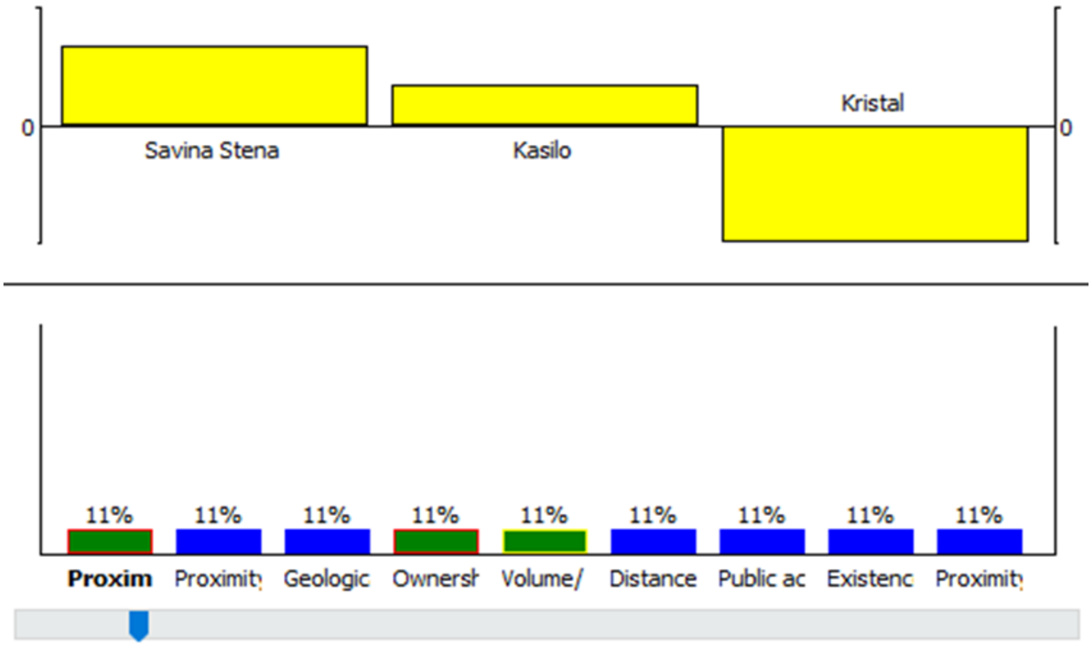


Figure 8. Walking Weights

This paper analyzes and ranks sites for the construction of a sanitary landfill based on the criteria of sustainable development. The result obtained by multi-criteria analysis of ranking the possibility of successful construction between the three proposed construction sites, based on nine selected criteria, using the PROMETHEE method showed a certain reality, which was consistent with the situation on the ground. Different preference functions were used depending on the criteria. The obtained results of NET flow, PROMETHEE diamond solutions, GAIA landfill site plan, Action profile for all alternatives, and sensitivity analysis of Walking Weights are presented. Based on the conducted analysis, the most adequate location for the construction of the sanitary landfill was Savina Stena, followed by Kasilo and Kristal. The application of the obtained results can be used in the decision-making process for spatial planning and development plans, as well as for solid waste management plans.

The application of the method for multi-criteria analysis of waste management plans should be an integral part of the overall management system to the highest level, because the implementation of environmental protection is an interactive process. In the case of a sanitary landfill, the capacity of the method for multicriteria analysis is demonstrated in the area of analysis and ranking of the landfill's impact on the surrounding ecosystem, economic benefits and society as a whole.

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Alati za donošenje odluka u izbor lokacije regionalne sanitarne deponije

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INFORMACIJE O RADU

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Ključne reči:
Višekriterijumska analiza
Izbor lokacije
Regionalna sanitarna deponija
Životna sredina

I Z V O D

U radu je primenjena inteligentna višekriterijumska analiza u cilju rangiranja kriterijuma u procesu izbora lokacije za Regionalnu sanitarnu deponiju. Analiza je obavljena za 3 unapred odabrane lokacije koje su odabrane na osnovu raspoložive površine, pristupa lokaciji, potencijalnih poteškoća u pripremi, pojave podzemnih voda, biodiverziteta i blizine urbanog područja. Ove lokacije su odabrane kao najpogodnije za izgradnju, kako sa inženjerskog tako i sa ekonomskog i ekološkog aspekta. Analiza je najbolji primer primene inteligentne višekriterijumske analize kao korisnog alata za upravljanje životnom sredinom u procesu donošenja odluka. Analiza je izvršena za tri predložene lokacije Regionalne sanitarne deponije: Kasilo, Kristal i Savina Stena, u opštinama Zvečan i Leposavić. Da bi se postigli što objektivniji rezultati, primenjene su PROMETHEE metode. Ovim metodama proračuna dobijena je sledeća rang lista lokacija za Regionalnu sanitarnu deponiju prema njihovoj podobnosti: Savina Stena, Kasilo i Kristal. Ovaj rezultat može doprineti procesu donošenja odluka o utvrđivanju strategije razvoja na lokalnom i regionalnom nivou.

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