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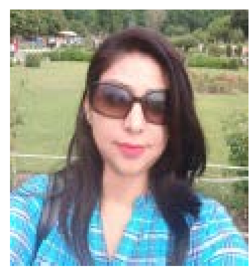

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A Review on Self-healing Concrete - A Biological Approach

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ABSTRACT

Concrete is one of the most popular and used construction materials. It is strong, durable, and relatively inexpensive, but it has a higher tendency to form cracks. The cracks provide a low service life for the concrete and high maintenance costs. The penetration of aggressive ions through cracks results in corrosion of steel reinforcement, carbonation, sulphate attack, alkali-aggregate reaction, etc. However, prevention of cracks formation is impossible, however, they can be controlled or repaired by various methods. Self-healing concrete is well known as a suitable remedial method to improve concrete's long-term durability. It is a new, rapid, and environmentally friendly approach. In this technology, when concrete is exposed to water, the healing agent material produces calcium carbonate ($CaCO_3$), which fills in the cracks and decreases permeability while enhancing concrete durability. The materials that are used as the healing agents are mostly bacteria, polymers, and chemical compounds. Bacteria are the most preferred material in concrete for healing. Therefore, bio concrete or bacterial concrete is another name for self-healing concrete. This article provides a comprehensive overview of self-healing concrete including, the system, process, mechanical properties, and durability of healed concrete.

1. Introduction

Concrete is the most well-known construction material globally because it is strong, durable, and it has low cost (Wiktor and Jonkers, 2011). Aggressive ions can enter concrete through cracks, which is a common property of the material. Concrete cracking is mostly caused by restrained deformation, external loads, and temperature gradients (Jonkers et al., 2010). Concrete is low in tensile strength, it cracks due to shrinkage, chemical reactions, etc (Luo et al., 2015). Khaliq and Ehsan (2016) stated that the deterioration of reinforced concrete resulted in high maintenance costs for both steel and concrete. Repairing cracks in concrete structures is required because cracks significantly affect service life and safety (Zhong and Yao, 2008). Therefore, to increase the service life of cracked concrete, it should be repaired.

Typically, two forms of crack repair are available; passive treatment and active treatment. In the passive treatment method, after detecting the cracks, repair agents are applied manually to the concrete, however, this method requires more effort and is costly. However, the active treatment method, also known as self-repair or self-healing, involves filling in the cracks without the assistance of humans.

Monitoring, detecting, and repairing are steps in the conventional repair process. Repair work can be done once the cracks have been found. A repair agent is applied from outside of the concrete and afterward it penetrates into the cracks. Repairing large cracks with

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this technology is quite suitable, but it is difficult for small and deep cracks. Therefore, an alternative repair method has been established which is called self-healing.

Self-healing concrete is a type of concrete that can repair its small cracks autonomously. It can prevent small cracks from developing into larger ones and is effective at healing deep micro-cracks (Wang et al., 2012). In the last ten years, numerous studies on the phenomenon of healing concrete have been conducted (Li and Yang, 2007). Only a few articles on self-healing concrete were published in the 1980s, but since the late 1990s, significant research has been done. Bacterial-concrete was developed by a microbiologist Dr. Henk Jonkers from the Netherlands during 2011. In this technology during concrete casting, some healing agents are added into the matrix. Later, if any cracks develop, the concrete's internal healing agents can be released by dripping into the cracks and sealing (Tziviloglou et al., 2016). Cracks can heal without any external human intervention. The healing is done only by activation of the healing agent which is released later during crack formation, thus bridging the crack openings.

The concept of self-healing in concrete was provided from the idea of the organic phenomena of organisms like plants and animals. Animals and trees can repair their own damaged skin on their own (Breugel, 2007). The healing agent is mostly calcium-based nutrients, also called calcium lactate with a small fraction of bacterial spores. The spores become active and the bacteria can access the bacterial substrate by activating to carbon dioxide (CO_2) when water flows into the cracks. Due to the calcium-rich environment and pH of 12 - 13 of the concrete, the formed CO_2 reacts with calcium ions resulting in the formation of calcium carbonates. Thus, bacterial development may cause the development of mineral precipitates in cracks, and significant reduction in the water permeability of the concrete (Vermeer et al., 2021).

The material using healing agents is mostly bacteria, polymers, and chemical compounds such as sodium silicate (Na_2SiO_3) and magnesium oxide (MgO). Since bacteria are the most commonly used healing agent, self-healing concrete is also called bacterial concrete or bio concrete. Siddique and Chahal (2011) stated that the bacteria's capacity to survive in an alkaline environment plays a crucial part in the selection of the bacteria. The majority of microorganisms will die and be unable to survive at a pH of 10 or higher. There are two distinct kinds of self-healing process: natural and artificial. In the natural process which is called autogenous, the cracks between 0.1 and 0.3 mm can be repaired by hydration of un-hydrated cement. But in an artificial process called autonomous, engineered admixtures are introduced to the concrete by chemical or biological methods. Biological methods are the youngest approaches among all self-healing designing methods. This article reviews the general concept, production mechanisms, and properties of self-healing concrete.

2. Self-healing concrete system

In concrete, self-healing systems can be divided into two categories: autogenic and autonomic (De Rooij et al., 2013).

2.1. Autogenic self-healing

It is an inherent material-healing characteristic where the process of self-healing starts with the currently available generic materials. For instance, the ability of cementitious materials to self-heal is caused by the property of hydration of the un-hydrated cement that remains on the crack surface (Neville, 2002).

In this system the volume of the healing product is limited. Concrete cracks that have been autogenously repaired come in sizes varying from 5 to 10 mm (Edvardsen, 1999; Aldea, et al., 2000), 100 μm (Jacobsen et al., 1996), 200 to 300 μm (Wiktor et al., 2011), and 0.05 to 0.87 mm (Gavimath, 2012). Because of a high content of un-hydrated cement at an early ages, autogenic self-healing has higher performance at this stage. Superplasticizer in engineered cementitious composite (ECC) can be used to lower the water/cement ratio while fibers can be used to control crack opening to improve the autogenic healing mechanism.

2.2. Autonomic self-healing

Unlike the autogenous healing system, this system requires the releasing of healing agent from a continuously formed vascular network or reserved encapsulation. The commonly used materials in autonomic self-healing mechanism can be categorized as bacteria, chemical compounds such as Na_2SiO_3, MgO, and polymers such as; superabsorbent polymers (SAP) and non-absorbent polymers. The healing capacity for this method is greater than the autogenic method.

3. Process of self-healing concrete

Concrete can undergo three different types of self-healing: natural, chemical, and biological self-healing.

3.1. Natural self-healing

As illustrated in Figure 1, there are several natural processes that can partially fix the concrete fracture. In natural processes, four different processes can block concrete cracks: (A) formation of $CaCO_3$ or calcium hydroxide ($Ca(OH)_2$) which block cracks; (B) cracks are blocked in the presence of water by some impurities; (C) cracks are further obstructed by hydration of un-hydrated cement or cementitious materials; and (D) cracks are prevented from forming by the development of hydrated cementitious pattern in the crack flanks (such as swelling of calcium-silicate-hydrate gel).

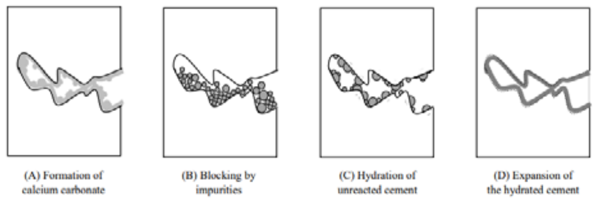

Figure 1. Mechanisms of natural self-healing in cementitious materials, adapted from Talaiekhozani and Abd Majid (2014)

One or more of these mechanisms may operate in parallel in many circumstances. Actually, the majority of these techniques are unable to completely fill the cracks; only some of them can. However, it is helpful to stop cracks from forming and the entry of harmful chemicals like acids introduced into the crack. $CaCO_3$ and $Ca(OH)_2$ formation is the most successful natural healing technique among the described techniques. The concrete's exterior surface in this mechanism has a white residue that is $CaCO_3$. On the exterior of the concrete, $CaCO_3$ can be seen as a white residue in this mechanism. The fundamental mechanisms for the production of $CaCO_3$ are described in equation 1-3.

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3{}^- + H^+ \leftrightarrow CO_3{}^- + 2H^+ \quad (1)$$

$$CO_3{}^{-2} + Ca^{+2} \leftrightarrow CaCO_3 \quad (2)$$

$$HCO_3{}^- + Ca^{+2} \leftrightarrow CaCO_3 + H^+ \quad (3)$$

The first step is started by dissolving CO_2 in the water, resulting in releasing CO_3^- ions. Next, these free CO_3^- ions react with Ca^{+2} released ions from cement hydration and form $CaCO_3$ crystals. Those developed crystals can grow, thus covering the cracks and filling the gaps. Actually, the second and third reactions can only occur at pH above 8 or within 7.5 and 8. Hence, it is needed to control the pH around these values. However, the natural process can only be used on concrete that is still quite young, and as concrete ages, the formation of $CaCO_3$ is likely what prompts self-healing. Natural self-healing is useful for cracks that are between 0.1 and 0.2 mm wide.

3.2. Chemical self-healing

Chemical self-healing is the term for artificial healing that involves adding chemicals to the crack to promote healing. In a small container, freshly mixed cement is combined with chemical liquid reagents (glue) to create the concrete. Two well-known chemical techniques are used to employ addition into concrete for self-healing.

3.2.1. Hollow pipettes and glue-filled vessel networks

Concrete can chemically self-heal in two different ways: (A) active mode and (B) passive mode. The glue is distributed in the active mode using a vessel network connected to an external supply. However, the glue in passive mode, which is not connected to any external glue source, is distributed using hollow pipettes, vessel networks, or capsules. Depending on the active or passive mode, either the vessel network or hollow pipettes can be utilized to create self-healing concrete. Different lengths of hollow pipettes have been used to create various self-healing materials, including polymers. It has glue mixed into it, which will rupture whenever cracks are growing and allow the glue to leak into the cracks, which will then heal them. A blood vessel in a creature served as inspiration for the design of self-healing pipettes.

Ethyl cyanoacrylate, methyl methacrylate, epoxy resin, and acrylic resin are a few types of glue that can be utilized to fill the pipettes in concrete (Homma et al., 2009).

Other than using hollow pipettes filled with glue for concrete self-healing. In order to distribute glue, Dry (1994) suggested using a network of vessels inside a concrete sample. A concrete specimen housed the delicate vessel network; one end of the network was attached to the glue supply, and the other end was sealed. Other researchers, including Mihashi et al. (2000) conducted a related study as well.

3.2.2. Encapsulated glue

Both macro and micro-scale applications are possible for glue encapsulation. The size of capsules at the micro-scale level varies from micro-capsules to nano-capsules. The concept of encapsulation is producing the capsules containing glue into the concrete for self-healing purposes. When the crack occurs, the glue is released from the capsules into the crack faces resulting in filling the cracks.

3.3 Biological self-healing

The use of microorganisms has been categorized as a biological strategy to design self-healing concrete (Siddique and Chahal, 2011; Wu et al., 2012). Nearly anywhere, including oil and water reservoirs, soil, acidic hot springs, and industrial wastewater, is a suitable environment for the growth of microorganisms. Several researchers have proposed using microorganisms to create self-healing concrete, including Bang et al. (2001), Jonkers et al. (2010), and Su et al. (2021). The three main categories of microorganisms are viruses, fungi, and bacteria. This technique involves pouring microbial broth right into the freshly mixed concrete. The additions could be distributed by vascular networks as described in the chemical method, or they could take the form of spores, capsules, immobilized forms on activated carbon or silica gel. A bacteria cannot grow in concrete because of its moisture content, temperature, or pH. As a result, in some situations a resistant type of bacteria (spores) is used instead of fresh microbial broth. Over 60 years is the maximum lifespan of some spores. It is also possible to use microorganisms that have been enclosed to withstand the harsh concrete environment, but this method is costly and difficult.

Another way to protect microorganisms from inappropriate conditions is using vascular networks for distributing the microbial broth throughout the cementitious matrix. However, this approach is difficult to implement and has poor constructability when using current technology. The best method in terms of the economical aspect was suggested to immobilizing of microorganisms on silica gel or activated carbon. However, it is still unclear how using these materials will affect the strengthening of concrete.

The most well-known and used healing agent in concrete is calcium-based nutrient also called calcium lactate $Ca(C_3H_5O_2)_2$, which is added to the concrete with a small amount of bacterial spores. The ratio of calcium lactate to the spores is commonly 2:1. When the bacteria come into contact with both water and oxygen, they begin to activate and can convert the available lactate to limestone ($CaCO_3$) resulting in filling the crack openings. Table 1 shows various types of bacteria with crack-healing capacity.

Selecting the type of microorganism is the first step of the process. If bacteria are chosen, the process will use one of two mechanisms to create self-healing concrete:

3.3.1 Precipitation of $CaCO_3$ (*Ureolytic process*)

The temperature of self-healing concrete can arise up to 70 ºC and its pH is between 10 to 13, also the water content reduces with drying the concrete. The selected bacteria need to be highly resistant to high temperature, pH, and serious limitations of water. In these conditions, mesophilic microorganisms typically cannot grow. Thermophilic bacteria were successfully tested by Ghosh et al. (2006) to create self-healing concrete to address this issue. During photosynthesis, hydrolysis, and surface reduction, microbial $CaCO_3$ may precipitate as a by-product. Gas and water permeability may be decreased by bacterial $CaCO_3$ precipitation on concrete surfaces. All over the world, carbonate precipitation occurs most frequently in the oceans. Because of their ability to increase the pH of the surrounding environment through a variety of bacterial metabolisms, bacteria are thought to have a major role in the precipitation of $CaCO_3$. One of the most popular biological ways is applying $CaCO_3$ using urolytic bacteria to design self-healing concrete. The shape of bacteria is commonly Bacilli, Cocci, or Spirilla. Different families of microorganisms, such as Mesophilic (Al-Thawadi, 2011) and Thermopilic (Ghosh et al., 2006), can be utilized in design of self-healing concrete. Among the shapes and types of bacteria, Bacillus pasteurii and sphaericus family are the most commonly used microorganisms.

It is clear that microorganisms, particularly bacteria, are capable of producing a variety of minerals, including phosphates, carbonates, and silicates (Fortin et al., 2018). $CaCO_3$ is one of the best fillers for concrete because of its high compatibility with cementitious compositions.

Calcium carbonate is produced through a series of biochemical processes (Stocks-Fischer et al 1999; Dick et al., 2006; Mitchell et al., 2010): 4) Urease-producing bacteria speed up the precipitation of calcium carbonate by hydrolyzing urea to produce ammonia (NH_3) and carbamic acid (NH_2COOH), 5) The carbamic acid spontaneously breaks down into one mole of ammonia and carbonic acid (H_2CO_3), 6) the carbonic acid decomposites, 7) As ammonia hydrolyzes, ammonium and hydroxide ions are produced, 8) As a result of the formation of hydroxide ions, the pH of the medium will rise, which promotes the production of bicarbonate (HCO_3^-) and carbonate ions (CO_3^{-2}), 9) During microbial metabolic activity, the negatively charged bacterial cell wall can draw positively charged calcium ions (Ca^{+2}) and deposit them on the cell wall surface, and 10) $CaCO_3$ is precipitated as a result of the reaction between the calcium and carbonate ions.

$$CO(NH_2)_2 + H_2O \rightarrow NH_2COOH + NH_3 \quad (4)$$

$$NH_2COOH + H_2O \rightarrow H_2CO_3 + NH_3 \quad (5)$$

$$H_2CO_3 \leftrightarrow HCO_3{}^- + H^+ \quad (6)$$

$$2NH_3 + 2H_2O \leftrightarrow 2NH_4{}^+ + 2OH^- \quad (7)$$

$$HCO_3{}^- + H^+ + 2NH_4{}^+ + 2OH^- \leftrightarrow 2NH_4{}^+ + 2H_2O + CO_3{}^{-2} \quad (8)$$

$$C_a{}^+ + Cell \rightarrow Cell^- Ca^+ \quad (9)$$

$$Cell^- Ca^+ + CO_3{}^{-2} \rightarrow CaCO_3{}^- Cell \downarrow \quad (10)$$

The rate of biological calcite precipitation is influenced by several factors such as: 1) concentration of the inorganic carbon content in dissolved solutions, 2) the rate of biological calcite precipitation, 3) concentration of calcium ions (Ca^{+2}), 4) pH, and 5) presence of nucleation sites (Li and Yang, 2007).

3.3.2. Polymorphic iron-aluminum-silicate precipitation (Silica process)

A complex iron-aluminum-silicate $[(Fe_2Al_3)(SiAl)O_{10}(OH)_5]$ precipitation was found in a lake contaminated with metal sediment, and it was located on the surface of isolated bacteria cells (Jonkers et al., 2010). In areas with acidic soils, the bacteria *Leuconostoc mesenteroides* play a significant role in the silica precipitation. This bacterium uses carbohydrates to produce lactic acid, which results in an acidic environment and lower colloidal silica solubility, which causes precipitation (Gollapudi et al., 1995). Due to the acidic condition, this method is not popular, also regarding the durability of concrete, it is not a good choice.

Table 1
Types of bacteria with crack-healing capacity in concrete

Types of bacteria	Crack-healing capacity	References
Bacillus pasteurii	Crack depth = 3.175 mm	(Ramchandran et al., 2001)
	Crack width = 3.18 mm Crack depth = 25.4 mm	(Bang et al., 2001)
Sporosarcinapastuerii, Bacillus sphaericus	-	(Kashyap, 2013)
Bacillus subtilisaureolytic	-	(Naveen and Sivakamasundari, 2016)
Bacillus megaterium	Crack depth = 4000 µm Crack width = 0.3 mm	(Su et al., 2021)
Bacillus sphaericus	Crack depth = 10 and 20 mm Crack width = 0.5 mm	(Van Tittelboom et al., 2011)
Bacillus subitilis	Crack width = 1-1.8 mm	(Huynh et al., 2017)
Bacillus cohnii	Crack width = 0.1-0.4 mm	(Xu and Yao, 2014)
Bacillus sp. CT-5	Crack width = 3.0 mm Crack depth =13.4-27.2 mm	(Achal et al., 2013)

4. Evaluating self-healing concrete

According to numerous research studies, self-healing concrete shows better behavior than conventional concrete without healing agents. Testing the self-healing concrete samples is necessary to ensure the property of the material compared to the normal concrete sample. Table 2 shows the most common techniques and methods used for evaluating self-healing concrete. The simplest way is evaluating visually either by the naked eye or using simple tools such as optical microscopy. Similar to conventional concrete, checking the material to resist various stresses such as; compression, tension, bending, etc. is required. In terms of durability, the self-healing concrete must be checked for various exposure conditions during its service life, for example; permeability and corrosion, etc. Testing the material for its microstructure is very important to ensure the healing performance at that level, tests such as; X-ray diffraction analysis, Scanning electron microscopy, etc. can be carried out. The combination of those tests can give an exact indication of the healing in the concrete.

Table 2
Concrete measurement techniques for self-healing performance

Self-healing evaluation technique	Methods	References
Visual observation	Digital image correlation Optical microscopy Crack sealing observation with eye	(Van Tittelboom et al., 2011)
Mechanical strength recovery	Compressive strength test	(Park et al., 2010; Abo-El-Enein et al., 2013; Xu et al., 2018)
	Tensile strength test	(Van Tittelboom et al., 2011)
	Three-point bend test	(Qureshi and Al-Tabbaa, 2014)
	Four-point bend test	(Snoeck et al., 2014)
	Impact loading slab	-
	Resonance frequency analysis	-
	Structural element deformation measurement	-
Durability	Air permeability	(Qureshi et al., 2018)
	Water permeability	(Van Tittelboom et al., 2011; Abo-El-Enein et al., 2013; Snoeck et al., 2014; Xu et al., 2018)
	Sorptivity/capillary water uptake Chloride permeability	(Siddique and Chahal, 2011; Achal et al., 2013; Sahmaran et al., 2013)
	Freeze-thaw test	-
	Corrosion test	-
	Neutron radiography	-
	Ultrasonic transmission measurement	(Van Tittelboom et al., 2011)
	Osmotic pressure	-

Table 2 continued
Concrete measurement techniques for self-healing performance

Microstructural evaluation	Environmental scanning electron microscopy (ESEM)	(Li et al., 1998; Jonkers et al., 2010)
	Scanning electron microscopy (SEM)	(Chahal et al., 2011; Abo-El-Enein et al., 2013; Sahmaran et al., 2013; Xu et al., 2018)
	X-ray diffraction analysis (XRD)	(Park et al., 2010; Chahal et al., 2011; Abo-El-Enein et al., 2013; Sahmaran et al., 2013)
	Energy dispersive X-ray spectrometer (EDS)	(Chahal et al., 2011; Abo-El-Enein et al., 2013; Sahmaran et al., 2013)
	X-ray radiography/tomography	-
	Infrared analysis	-
	Thermogravimetric analysis (TGA)	(Qureshi et al., 2018)
	Raman spectroscopy	-

4.1. Mechanical properties

Mechanical properties mainly include compressive, shear, flexural (three-point bending and four-point bending), and tensile strength of concrete. The ability of a material to resist a compression load is known as its compressive strength. Compressive strength is the most crucial factor in structural design and concrete quality control among mechanical properties. Normal concrete has a 25-50 MPa range for its compressive strength. Ordinary concrete continues to be constructed using self-healing technology.

The ability of a material to resist deformation while under load is known as its bending strength, and it corresponds to the material's maximum internal stress at the time of rupture. Two different bending tests exist, both the three- and four-point bending tests. The uniform stress area under the center loading point in a three-point bending test is relatively small and concentrated there. In the four-point bending test, the region of uniform stress is located between the inner span loading points. Numerous research studies can be found which achieved an amount of regain in compressive strength of concrete by self-healing. They tested the samples before and after healing and the regain strength efficiency of the healed concrete was present. The compression test results of some studies when the different types and concentrations of bacteria were used are collected in Table 3. For most of these studies, the temperature of the media was about 25 ºC, which is a suitable degree for bacterial activation.

Other researchers used various polymers as concrete healing agents. After testing the samples using various methods, they could achieve good results in terms of sample strength improvement, Table 4. Healing agents such as sodium silicate (Na_2SiO_3) and magnesium oxide (MgO) were used by previous researchers for the purpose of healing the concrete, Table 5.

Table 3
Compressive strength improvement caused by different bacteria

Type of bacteria	Concentration	pH of media	Test methods	Regain efficiency	References
Bacillus megaterium	30×10^5 cell/ml	6.5	Compression	24 %	(Andalib et al., 2016)
Sporoscarcina. pasteurii	5.2×10^7 cell/ml	8.6	Compression	12 %	(Ramchandran et al., 2001)
Sporoscarcina. pasteurii	-	9.25	Compression	33 %	(Abo-El-Enein et al., 2013)
Sporoscarcina pasteurii	10^3 cell/ml	-	Compression	22 %	(Chahal et al., 2012)
Bacillus subtilis	0.33 cell/ml	8	Compression	14.8 %	(Pei et al., 2013)
Bacillus subtilis	10^5 cell/ml	-	Compression	19.2 %	(Vempada et al., 2011)
Bacillus cereus	10^6 cell/ml	8.5	Compression	38 %	(Maheswaran et al., 2014)
Shewanella sps	10^5 cell/ml	7.2	Compression	25.3 %	(Ghosh et al., 2005)
Bacillus subtilis	2.8×10^8 cell/ml	-	Compression	12 %	(Khaliq and Ehsan, 2016)
Bacillus sp. CT-5	Optical density (OD_{600} of 1)	8	Compression	36.15 %	(Achal et al., 2013)
Bacillus sphaericus	-	-	Compression	14.3 %	(Gandhimathi and Suji, 2015)
Bacillus sphaericus	-	10 - 11	Compression	11.2 %	(Gavimath et al., 2012)

Table 4
Strength improvement from various types of polymers

Type of polymers	Methods	Test methods	Efficiency	References
Epoxy resin	Microcapsules	Compression	1.9 time normalized strength	(Li et al., 2013)
		Three-point bending	1.3 time normalized strength	
Polyurethane	Encapsulation	Three-point bending	54 % improvement in strength and 52 % stiffness	(Van Tittelboom et al., 2011)
Polyurethane	Encapsulation	Three-point bending	35 % stiffness	(Feiteira et al., 2016)
Superabsorbent polymers (SAP)	-	Three-point bending	8 % improvement in strength	(Gruyaert et al., 2016)
Methyl methacrylate monomer	Micro-encapsulation	Compression	30.4 % improvement in strength	(Yang et al., 2010)

Table 5
Strength improvement of concrete by using sodium silicate (Na_2SiO_3) and magnesium oxide (MgO)

Healing concrete	Methods	Test methods	Efficiency	References
By using sodium silicate (Na_2SiO_3)	Mixed with concrete	Three-point bending	5 % improvement in compressive strength	(Qureshi and Al-Tabbaa, 2016)
	Encapsulated	Three-point bending	6 % load regain	(Qureshi et al., 2016)
	Encapsulated	Three-point bending	12 % load regain	(Kanellopoulos et al., 2015)
By using magnesium oxide (MgO)	Encapsulated	Three-point bending	17 % load regain	(Kanellopoulos et al., 2015)
	Micro-encapsulated	Ultrasonic wave transmission	12.3 % specific stiffness regain	(Mostavi et al., 2015)
	Micro-encapsulated	Three-point bending	26.2 % flexural regain	(Pelletier et al., 2010)

Alkali-resistant bacteria that produce spores were used by Luo et al. (2015) in their investigation into self-healing concrete. The results demonstrated a reduction in crack width with increasing repairing time, Figure 2. Additionally, bacteria were used as a healing agent in concrete by Gavimath et al. (2012). The samples were then examined for tensile and compressive strength in both normal and healed concrete. Bacterial concrete samples outperformed the controls in terms of strength, Figure 3.

4.2. Durability

For concrete structures, durability is the main concern because it has to do with the material's service life. Durable concrete means resisting or penetrating any aggressive ions into the concrete. Sulphate resistance, alkali-aggregate reaction, steel reinforcement corrosion, and carbonation are the main factors of concrete deterioration. Deterioration of concrete mainly occurs by being permeable. A system of self-healing is a novel technique used to make the concrete more durable by bridging the cracks, thus resisting opening and making the concrete impermeable.

The durability of self-healing concrete can be assessed and verified using a variety of test methods. Table 6 shows various studies which used different healing materials and then tested the samples for water absorption, their results showed a significant reduction in porosity.

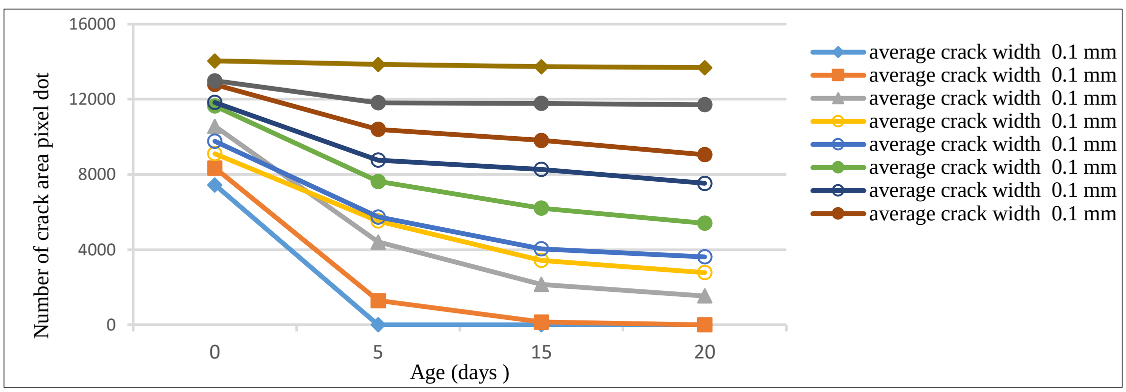

Figure 2. Number of crack area versus average crack width with time (Luo et al., 2015)

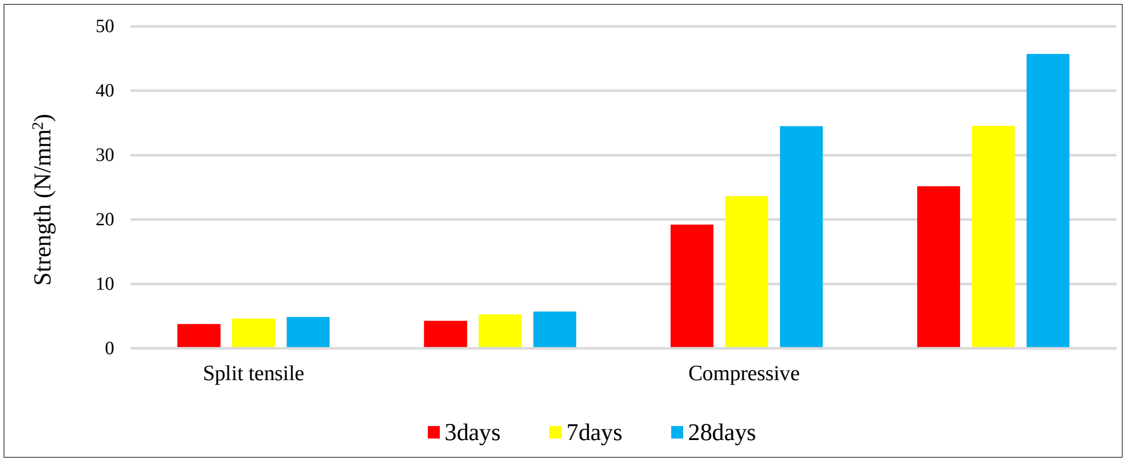

Figure 3. Strength comparison in control and bacterial concrete (Gavimath et al., 2012)

Table 6
The effect of various healing materials on water absorption after cracking

Type of healing materials	Methods	K-value untreated	k-value treated (healing agent)	Efficiency factor	References
Polyurethane in ceramic capsule	Water entering a repaired crack	1×10^{-6}	1×10^{-12}	2	(Van Tittelboom et al., 2011)
Bacillus. sphaericus with hydrogel	Water entering a repaired crack	1×10^{4} - 1×10^{5}	1×10^{5} - 1×10^{6}	1.25	(Wang et al., 2014)
Superabsorbent polymers (SAP)	Water entering a repaired crack	1×10^{-6}	1×10^{-10}	2	(Snoeck et al., 2014)
Bacillus. sphaericus immobilized in polyurethane	Water entering a repaired crack	1×10^{-5}	1×10^{-10}	2	(Wang et al., 2012)
Bacillus. sphaericus in sol gel+$CaCl_2$	Water entering a repaired crack	1×10^{-4}	1×10^{-12}	3	(Van Tittelboom et al., 2010)

Achal et al. (2013) investigated how healing mortar samples were impacted by Bacillus sp. CT-5. The samples' porosity was examined and contrasted with the control samples' porosity percentage. Figure 4 shows the reduction in porosity of self-healed mortar samples.

The durability of self-healing concrete was also investigated by Tziviloglou et al. (2016). The mortar samples were examined for water permeability. Healing agents were used in some of the samples and then compared to the controls. According to their research, samples that had been healed had much lower water leakage than samples that had not been healed, Figure 5.

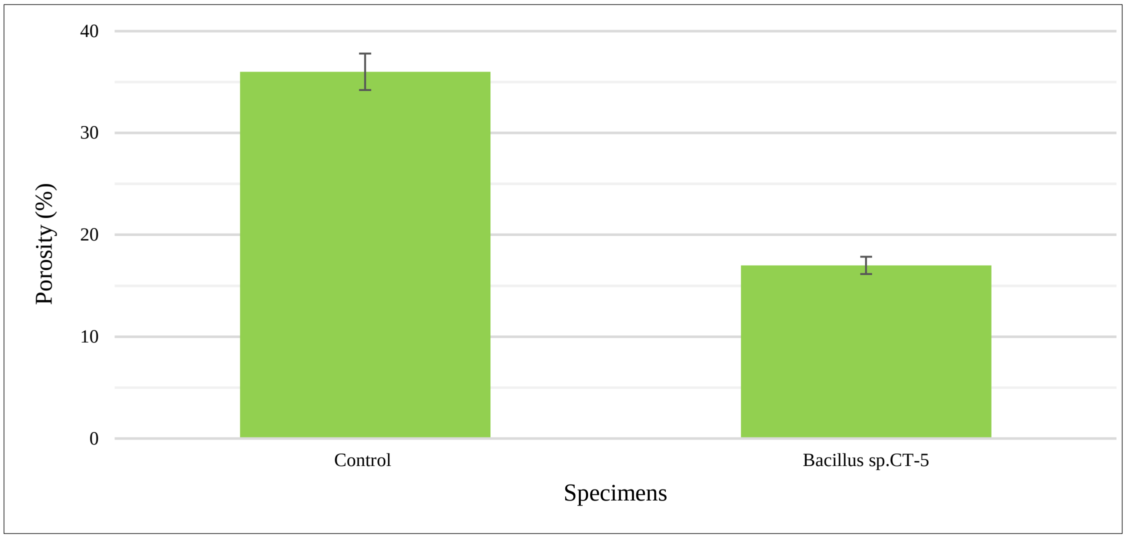

Figure 4. Comparison of total porosity in control and Bacillus sp. CT-5 bacterial mortar (Achal et al., 2013)

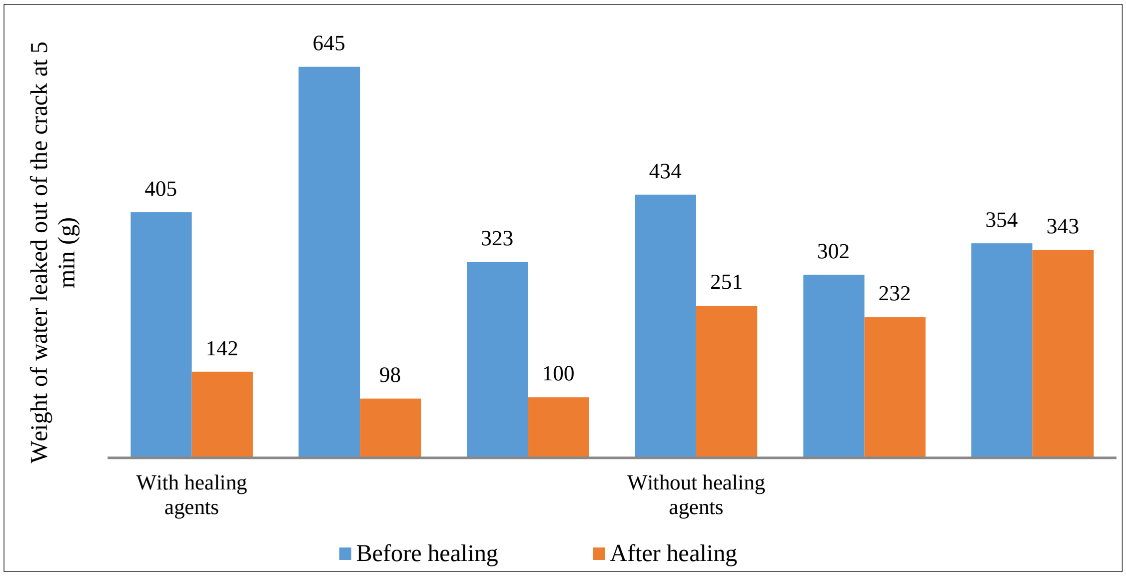

Figure 5. Effect of healing agents on mortar specimens' permeability both before and after healing (Tziviloglou et al., 2016)

4.3. Microstructural evaluation

Microstructural evaluation is needed for healed crack visualization, crystal materials determination, deposited crystal visualization, etc. There are a lot of evaluation techniques that are used for microstructural measurement of self-healing concrete, such as X-ray diffraction, scanning electron microscopy, energy dispersive spectrum, etc. Majority of the research studies on self-healing concrete have tested the samples for analyzing their microstructures besides testing for mechanical properties and durability such as strength, permeability, corrosion, etc.

Khaliq and Ehsan (2016) prepared four concrete mixtures. The mixture was the same in all but incorporation techniques of the bacteria were different in all. The first one was a control mix without adding bacteria. While for the second mix, the bacteria were added directly to the water during mixing the concrete. However, nanoplatelets were utilized for the third and fourth mix carrier compounds, such as light aggregate and graphite, respectively. The formation of $CaCO_3$ for all mixes through scanning electron microscopy analysis was observed, Figure 6.

Furthermore, Tziviloglou et al. (2016) used EDS analysis on the crystalline formation to check the formation of $CaCO_3$. High peaks of calcium (Ca), carbon (C), and oxygen (O) were detected in the test results, indicating that $CaCO_3$ was in fact present. Gruyaert et al. (2016) used scanning electron microscopy (SEM) to check the healing process on mortar specimens using SAP as a healing agent, Figure 7. Qureshi et al. (2018) used ESEM, XRD, and TGA analysis to check the healing performance. The crack width before healing was 0.17mm, and after 28 days of healing was reduced to 0.14mm, Figure 8.

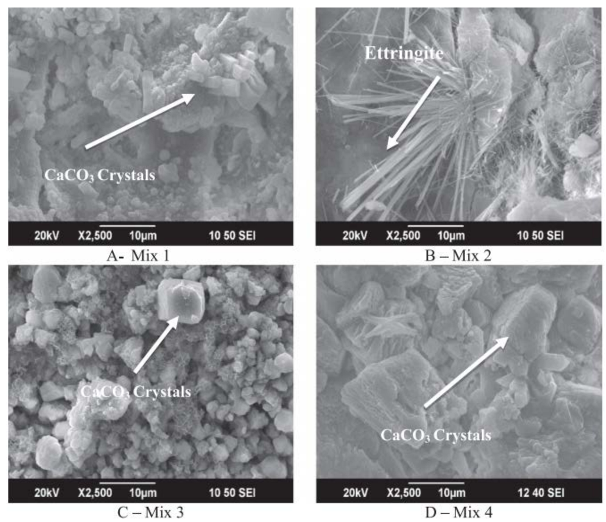

Figure 6. Magnified Scanning Electron Microscopy; analysis of 28 days of samples before cracking (Khaliq and Ehsan, 2016)

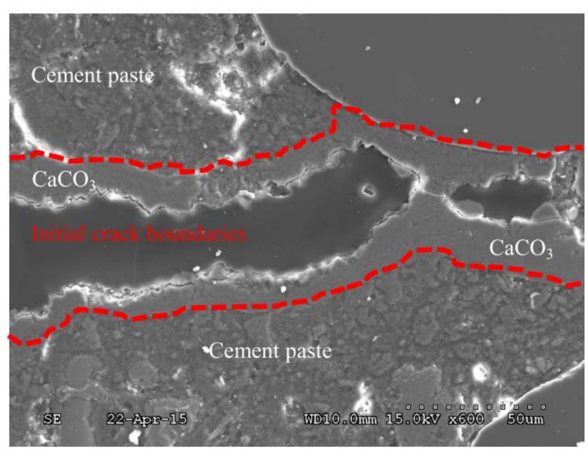

Figure 7. SEM for a mortar specimen with cracks and some healing that contains SAP (Gruyaert et al., 2016)

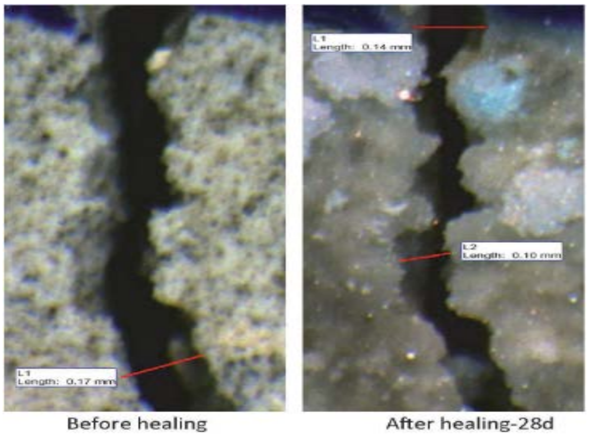

Figure 8. Crack width comparison of cement mix before and after healing by ESEM analysis (Qureshi et al., 2018)

5. Advantages

In a summary, the main advantages of self-healing in concrete can be drawn as:

1. Improvement of the compressive strength of concrete.
2. Remedying cracks quickly.
3. Reduction in corrosion of reinforcement.
4. Reduction in permeability of concrete.
5. Increasing the durability of concrete.
6. Eco-friendly, natural and it is pollution free.
7. Lower repair and maintenance costs.
8. Decreasing production of concrete.
9. Through this solution system, the aesthetic appearance is not harmed.
10. Better resistance to freezing-thawing.
11. Reducing CO_2 emission from concrete production.

6. Disadvantages

Despite the advantages explained, the self-healing approach has some disadvantages in various manners such as:

1. The price of bacterial concrete is higher; it is almost twice as expensive as regular concrete.
2. In any environment or medium, bacterial growth is insufficient. The cultivation of calcifying microorganisms involves the use of a variety of nutrients and metabolic products that influence the survival, growth, biofilm, and crystal formation of the organisms. A lot of research has been conducted on the metabolic products and retention of nutrients in building materials.
3. No IS code is provided yet because it is a new research material, therefore it is difficult to get optimum performance when the bacteria are used in concrete.
4. The cost of the investigation process will be high because bacteria have different properties thus they contribute to different behavior. Therefore, some testing methods are needed to investigate the microstructure of the concrete such as SEM, which is costly, and good skill to carry out the test are required as well.
5. The self-healing agent, which accounts for 20 % of the concrete volume, is carried by the clay pellets.

7. Applications

Using of bacterial concrete has become increasingly popular, it can be used for:

- Healing of concrete cracks and
- Repairing of monuments constructed in limestone.

Also for:

- Durable roads with low cost,
- River banks,
- High - strength buildings, and
- Durable housing with low cost.

For creating self-healing concrete, a number of processes have been proposed. It has not yet been used in all new constructions, and self-healing bacteria-based concrete is still in the early stages of development.

8. Conclusions

Based on reviewing various research study articles on self-healing concrete, some points can be drawn. Self-healing is a novel strategy that can be used to remediate the cracks in concrete internally when they start to grow. Since cracking is the main problem in concrete structures, it cannot be prevented, but controlling and repairing the cracks is necessary. Externally remediating the cracks on the concrete surface is one of the classic techniques, and it requires special materials, machines, and skilled labor. Hence, self-healing is a good alternative to classical repairing. Self-healing concrete needs some material as a healing agent, and bacterial spore is usually used and added to the concrete during mixing. By reducing permeability, this technology significantly improves the durability of concrete. It can also reduce inspection labor, maintenance cost, and cement production by providing safer and more sustainable material. Despite the positive results of self-healing, the application of self-healing concrete in all engineering constructions is still quite limited because of a few drawbacks, most notably economic ones. The optimum volume fraction of the bacteria is still unknown, and there is no design code to produce appropriate bacterial-healing concrete. Self-healing concrete is an interested subject for research studies, the concept can be improved by using other materials and using new technology in order to withstand the small detect.

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Osvrt na samozaceljujući beton - biološki pristup

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INFORMACIJE O RADU

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Samoisceljivanje
Pukotine
Bakterije
Bacillus
Bakterijski beton
Trajnost

I Z V O D

Beton je jedan od najpopularnijih i najviše korišćenih građevinskih materijala zbog svoje čvrstoće, izdržljivosti i relativno niske cene, ali on ima i veću tendenciju za stvaranje pukotina. Pojava pukotina smanjuje vek trajanja betona i povećava troškove održavanja. Prodiranje agresivnih jona kroz pukotine dovodi do korozije čelične armature, karbonizacije, stvaranja sulfata, alkalno-agregatne reakvije, itd. Međutim, sprečavanje nastanka pukotina je nemoguće, ali one se mogu kontrolisati ili popraviti brojnim metodama. Samozaceljujući beton je poznat kako prikladna metoda za ispunjavanje pukotina, kao i za poboljšanje dugoročne trajnosti betona. To je nov, brz i ekološki prihvatljiv pristup. U ovoj tehnologiji, kada je beton izložen vodi, materijal za popunjavanje stvara kalcijum karbonat ($CaCO_3$) koji ispunjava pukotine i smanjuje propustljivost, a produžava trajanje betona. Materijali koji se koriste za popunjavanje pukotina su uglavnom bakterije, polimeri i hemijska jedinjenja. Bakterije predstavljaju najpoželjniji materijal za ovaj postupak. Zbog toga, drugo ime koje se koristi za samoisceljujući beton glasi biobeton ili bakterijski beton. U ovom radu je predstavljen pregled tehnologije samozaceljujućeg betona koji obuhvata sistem, proces, mehanička svojstva i trajnost ovog betona.

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Circular Economy Use of Biomass Residues to Alleviate Poverty, Environment, and Health Constraints

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ABSTRACT

Inadequate energy and water resources supply are major constraints contributing to poverty and poor health outcomes in developing economies. Low-income countries lack ready access to modern necessities such as electricity and potable water. On one hand, the scarcity of electricity and other clean energies compel reliance on traditional biomass for domestic fuels. On the other hand, harvesting firewood to meet energy needs leads to deforestation and environmental degradation. Furthermore, burning the wood for heat creates ecosystem perturbators such as toxicants, greenhouse gasses, and particulate matter. These pollutants portend adverse health concerns, including premature mortality. Globally, fine particulate matter air pollution alone causes about 3.3 million deaths annually. The contribution of this paper is to offer how circular economy targeted technologies could come to the rescue. In particular, utilizing biomass residues and wastes for briquette and pellet creation is highlighted. These densified fuel products could serve as green energies in domestic and industrial applications; and thus, help to attenuate poverty, and the adverse environmental and health consequences of traditional biomass.

1. Introduction

Most of the energy consumed on planet earth today is still fossil fuels based. As of 2018, fossil fuels account for 85 % of the global primary energy supply. In 2020, renewable energies accounted for only 22.1 % of the total ultimate energy consumed in Europe (EurObserv'ER, 2021). This circumstance imposes energy insecurity because, fossil fuels are finite, depleted, nonrenewable and therefore unsustainable. Also, fossil fuels exert unwanted external costs to the environment such as the contamination of air, soil, and water resources. Perhaps one of the most ominous effect of fossil energy is the potential to perturb the global climate with the emission of greenhouse gases (GHGs). To preserve humanity and natural resources, a more environmentally friendly energy source is needed.

Renewable energy could play a role and stand proxy for fossil fuels. Among renewable energy sources, traditional biomass (such as agricultural residues, dung, and firewood) is used extensively in low-income countries. In 2020, approximately 1.93 billion m^3 of wood fuel were produced in the world. Africa and Asia accounted for 74 % (each contributing 37 %), followed by Americas (17

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%). In the same year, about 53.6 million tons of wood charcoal were also produced globally. Africa accounted for 65 %; and the Americas and Asia each accounted for about 17 % (WBA, 2021). However, traditional biomass is encumbered by some of the limitations of fossil fuels, for instance, GHGs and particulate matter emissions. In the contribution made with this paper, some unwanted external costs associated with traditional biomass are highlighted, and solutions to mitigate them are presented.

2. Traditional biomass

The oldest of all fuels is arguably biomass. When primordial Homosapien invented fire, the spark was likely nurtured into flame and sustained with traditional biomass (dry grass, leaves, and twigs). These biomasses, as well as others like charcoal, firewood, husks, stalks, cobs, shells, and animal dung, are routinely used as biofuel today. About 2.5 to 3 billion people worldwide depend on traditional biomass for energy (IEA, 2017; Lello, 2022; Rakos, 2022). This population relies on biomass as the primary energy source to boil water, cook food, and warm homes. In Sub-Saharan Africa (SSA), traditional biomass supplies over 80 % of primary energy for more than 90 % of the population. In Kenya, charcoal provides 34 % and 82 % of energy needs respectively for rural and urban dwellers (Njenga et al., 2014). In Turkey, 60 % of energy for the paper industry comes from wood wastes, and about 6.5 million households use wood for heating (Baris and Kucukali, 2012). Types of biomass utilized as fuel have been enumerated in published literature (Demirbas, 2004; Tumuluru et al., 2011; Bajwa et al., 2018; Pradhan et al., 2018; Hao, 2020; Coad, 2021; Kedia, 2021; Rakos, 2022). In 2018 about 85 % of the 55.6 EJ global domestic energy supply originated from solid biofuels (WBA, 2020). However, there are costs associated with the use of traditional biomass.

3. Unwanted external costs

The unwanted external costs of traditional biomass pervade a broad range of areas and resources. The burden impact crucial sectors essential for human existence such as the ecosystem, food, housing, health, soil, and agricultural productivity. Perhaps the most visible route that represents a burden in many developing countries is the degradation of air quality.

4. Air pollution

Air pollution is a prominent level 2 risk factor. This is within the level 1 risk factor of environmental and occupational risks that constitute a lion's share of the global burden of disease and premature mortality. Environmental and occupational risks registered the highest exposure values in the past three decades, with mean summary exposure values (SEVs) of 52.55, 48.50, and 45.36, respectively, for the year 1990, 2010, and 2019. In comparison to another level 1 risk factors, behavioral risks had mean SEVs of 16.80, 15.38, and 15.09, respectively, for the said time frame, while those for metabolic risks were 14.90, 19.40, and 22.14. The SEVs are measured on a 0 to 100 scale. A 0 is when the entire population is exposed to a minimum risk, and a 100 is when the population is exposed to a maximum risk (Murray et al., 2020).

Air quality may be degraded by suspended matter and particulates. Air-borne particulates of public health interest are usually defined as particles with an aerodynamic diameter less than 10 µm (PM_{10}), with those with diameters less than 2.5 µm ($PM_{2.5}$) further categorized as fine particles. Particulates include black carbon/soot, dust, nitrates, sulfates, and ozone. Ammonia (NH_3) is a particulate matter precursor. The abundance of NH_3 is often considered the limiting criterion in the formation of, and pollution by $PM_{2.5}$. Although chemical fertilizers and animal husbandry are the main sources of anthropogenic NH_3 emissions, the burning of biomass contributes to the problem (Dentener and Crutzen, 1994; Galloway et al., 2004). Over the 14-year period (2002 - 2016), significant increments in atmospheric ammonia were observed around the world, e.g. in Africa (Egypt, Ghana, Guinea, Nigeria, Sierra Leone), Asia (Bangladesh, Cambodia, China, India, Pakistan, Uzbekistan, Vietnam), Europe (Denmark, Germany, Italy, Netherlands), and the Americas (Brazil, Colombia, Ecuador, Peru, USA). Increasing trends in mean yearly NH_3 concentrations of about 1.83, 2.27, and 2.61 percentage points for the EU, China, and the USA were reported, respectively (Warner et al., 2017).

Particulate matter air pollution may occur from combustion processes via wild, domestic/ residential and industrial actions, and from vehicular traffic/ transportation functions. Examples include forest fires, burning of traditional biomass for domestic reasons, and combustion of fossil fuels for air, land, and sea transportation (Pennise et al., 2001; Edwards et al., 2003; IEA, 2017). Between 1983 and 1984, about 3.7 million hectares of forest were burned around Kalimantan and neighboring Sabah in Indonesia (Repetto et al., 1989). Citing the European Forest Fire Information System (EFFIS), Horton and Palumbo (2022), reported that for the first 197 days of the year 2022 (as of 16 July 2022), almost 346,000 hectares of land were burned by wild fires in the European Union. Other authors have reported on the combustion characteristics of different types of biomass (Haykiri-Acma, 2003; Demirbas, 2004; Hao, 2020; Suman et al., 2021), and on the emission factors for biomass and fossil fuel-fired stoves (Gaegauf et al., 2001; Bhattacharya et al., 2002; Johansson, 2002; Edwards et al., 2003; Boman et al., 2004; Sippula et al., 2007; Bäfver et al., 2011; Njenga et al., 2014; Obaidullah and De Ruyck, 2021).

Combustion operations create unwanted external costs. Annually, about 2 Mt of carbonaceous aerosol pollutants are pumped into the Asian atmosphere, forming the

"Asian dark cloud" (Laghari, 2013). Carbonaceous aerosols can absorb solar energy and heat the atmosphere (Teng et al., 2012), resulting in the melting of ice and glaciers. During the period 2003 - 2009, about 174 Gt of water were estimated to have been lost by the Himalayan glaciers; and contributed to floods that affected human life, water supplies, and hydroelectric power across the region. In 2010, for example, seasonal melt and excessive monsoon rains caused the loss of 2000 lives and billions of dollars in economic damage in Pakistan (Laghari, 2013). In July 2022, forest and wild fires raged across the world, in Europe (France, Greece, Italy, Portugal, Spain, etc.), and in several states in the USA (e.g., California, Oregon, New Mexico, Texas, and Washington); spewing to the atmosphere, huge amounts of heat energy, particulate matter, smoke, and other pollutants with environmental and health consequences. Pollutants released by the combustion of traditional biomass pose adverse health implications. Each year, over 4 million premature deaths globally are associated with air pollution from cooking on open fireplaces (Lello, 2022; Rakos, 2022). About 2.5 to 2.8 million of these deaths are thought to emanate from indoor air pollution (IEA, 2017; Ohlson, 2022). In India, 25 % of black carbon emissions come from household energy use, and about 25 % of deaths due to $PM_{2.5}$ is attributed to residential biomass burning (Kokil, 2022a). Implications of combustion particulate matter air pollution have been reported for Jakarta, Indonesia (Ostro, 1994), Cairo, Egypt (Raufer, 1997), Santiago, Chile (Eskeland, 1997; Zegras and Litman, 1997), and Oslo, Norway, (Rosendahl, 1998). Table 1 lists more burdens that may emanate from burning processes and traditional biomass exploitation.

Table 1
Unwanted external costs attributable to traditional biomass and combustion operations

S/N	Cost description	Reference
1	Annually, 17 million hectares of rain forest are destroyed globally due to wood harvesting, animal husbandry, etc.	Baroni et al., 2007
2	From 1980 to 2000, about 100 million hectares of tropical forest (≈ 50 % intact ecosystems) were lost to agricultural expansion (plantations, ranching, etc.)	IPBES, 2020
3	Across the 21 countries with detailed records, the expansion of invasive alien species has risen by about 70 % since 1970; and global terrestrial habitat integrity reduced by 30 % due to habitat loss and deterioration	IPBES, 2020
4	In 1983-1984, biomass combustion (3.7 million hectares of forest fires burned around Kalimantan and neighboring Sabah) in Indonesia was conservatively estimated to cost about US$ 3.5 billion in timber assets.	Repetto et al., 1989
5	Each year, costs of public and environmental health losses related to soil erosion in USA exceed US$ 44 billion	Pimentel et al., 1995
6	In Oslo, Norway, particulate matter air pollution due to transportation reduced life expectancy by about 0.9 years, with the social costs estimated at Nkr 3,600 (US$ 481.19) per capita	Rosendahl, 1998
7	Unwanted external costs of agriculture in USA per annum were estimated at US$ 5.7-16.9 billion. The damages incurred by sub-categories were (in million US$): water resources, 419.4; soil resources, 2,242.7-13,394.7; air resources, 450.5; wildlife and ecosystem biodiversity, 1,144.9-1,174.1; and human health, 1,425.4-1,450.5	Tegtmeier and Duffy, 2004
8	Adverse health effects account for over 95 % of external costs associated with particulate matter, nitrogen and sulfur dioxides	Eshet et al., 2006
9	Fine particulate matter ($PM_{2.5}$) is a significant risk factor in low birth weight	Tu et al., 2016
10	A minimum of 42 % of all lower respiratory infections is attributable to environmental pollution in developing countries. Solid fuel uses alone account for 36 %	Prüss-Üstün and Corvalán, 2006
11	Health losses associated with airborne particulate matter in the EU is estimated at € 90-190 (US$ 105.758-223.266) billion per year	Van Grinsven et al., 2006
12	In the USA, the cost of premature mortality from fine particulate matter ($PM_{2.5}$) associated with food export was reported to be US$ 36 billion per year (in 2006 US$). The mean mortality rate ratio from lung cancer and cardiopulmonary disease associated with these fine particulates was estimated to be 1.26	Paulot and Jacob, 2014; Dockery et al., 1993
13	One report estimated global economic losses of food crops due to ozone pollution at US$ 11-26 billion per annum. Ozone is formed by precursors such as nitrogen oxides and carbon monoxide. The precursor gasses are however generated by the burning of fossil fuels and biomass	Mills and Harmens, 2011; Wallack and Ramanathan, 2009
14	Global impact of fine particulate matter ($PM_{2.5}$) pollution has been estimated at 3.3 million deaths annually	Lelieveld et al., 2015
15	In 2002, the global death burden from environmental, diarrheal and respiratory diseases was over 16.5 million persons. In 2015, the impact of diseases caused by all pollutions was estimated at 9 million premature deaths (16 % of all deaths worldwide). The global impact of all pollution on welfare was reported to inflict a loss of 6·2 % of world economic output (≈ US$ 4·6 trillion) per year	Prüss-Üstün and Corvalán, 2006; Landrigan et al., 2017

5. Mitigation technologies

As Table 1 highlights, burdens associated with anthropogenic exploitation of traditional biomass are tremendous. With the increasing global population, these problems will accentuate in the future unless measures to attenuate them are implemented. A number of technologies such as anaerobic digestion (Aso et al., 2019; Aso, 2022); hydropower (IHA, 2022); solar, wind, and other renewable energy sources (EurObserv'ER, 2020; 2022), could be employed as mitigation interventions. In the next section, two related technologies (briquettes and pellets) that could be used are presented.

6. Briquettes and pellets

The efficiency of biomass in open fire combustion is low (≈ 5-15 %). With charcoal, energy is wasted in the carbonization process. Yet, > 36 Mt of charcoal valued at $US 11 billion were produced in SSA in 2012 (Lello, 2022); while globally, 53.6 Mt of wood charcoal were produced in 2020 (WBA, 2021). Also, traditional biomasses have low bulk density; a characteristic that reduces energy content per unit volume, and exacerbates handling, storage and transportation costs. Densification circumvents these limitations. Briquetting and pelleting are two methods used to densify solid biomass, and could serve as vehicles for fuel in domestic and industrial applications. Briquettes and pellets could be used to fire boilers, cook stoves and gasifiers, and as feedstock to generate heat, or power, or combined heat and power (CHP). The worldwide production of densified biofuel increased from < 7 Mt in 2006 to > 26 Mt in 2015 (Kang et al., 2019). In the year 2018, solid biofuels accounted for 60 % of the 226 TWh of biopower produced as CHP (WBA, 2020).

Briquettes and pellets may differ in size, shape and moisture content. Pellets are generally produced from finely ground ingredients, and are usually of smooth cylindrical configuration with a length of 18-24 mm; diameter 6-8 mm; unit density 560-1,190 kg/m^3; and moisture content 8-18 %. On the other hand, briquettes could be densified from larger-sized ingredient particles with a wider range of moisture contents; and produced as cylinders, cuboids, hexagons, logs, sticks, and other shapes. Briquettes can range in length from 60-200 mm, diameter 50-100 mm, unit density 320-1,000 kg/m^3, and moisture content 10-30 % (Tumuluru et al., 2011; Balan et al., 2013; Bajwa et al., 2018; Brunerová et al., 2018). Figure 1 is a pictorial representation of sample briquettes and pellets.

7. Briquettes and pellets production machinery

Briquettes and pellets may be produced from many kinds of biomass. Perhaps the availability and versatility of biomass feedstocks enabled the application of densification technology all over the world. Examples include reports from Brazil (Rousset et al., 2011), Chile (Hernández et al., 2019), China (Hao, 2020), Congo (Fodor, 2022), Gabon (Fodor, 2022), India (Kedia, 2021; Kokil, 2022 b), Indonesia (Susastriawan and Sidharta, 2014), Malaysia (Chin and Saddiqui, 2000), Nigeria (Olorunnisola, 2007; Onuegbu et al., 2012; Zubairu and Gana, 2014; Onukak et al., 2017), Poland (Stolarski et al., 2016), Tanzania (Sjølie, 2012), and Zambia (Ohlson, 2022; Peterson and Klingenberg, 2022; Stahl, 2022). A review of the briquette value chain in some African countries (including Kenya, Rwanda, and Uganda) was reported in 2016 (Asamoah et al., 2016). A systematic review and life cycle assessment of biomass pellets and briquettes production in some Latin American countries (including Colombia, Costa Rica, and Mexico) was reported in 2022 (Silva et al., 2022).

In order to manufacture briquettes and pellets, several production systems may be deployed. The machinery may range from rudimentary, laborious, and drudgery-intensive operations: wood is harvested and transported on wheelbarrows manually (Njenga et al., 2014), and recycled containers are used to manually mold the briquettes into shapes (Asamoah et al., 2016); the use of manually operated piston and die presses that could generate pressures of 1.2-7.0 MPa (Chin and Saddiqui, 2000; Olorunnisola, 2007; Onuegbu et al., 2012); the use of small scale briquette extruder powered by 4.103 kW gasoline internal combustion engine (Susastriawan and Sidharta, 2014); and the use of large scale industrial machines with capacities of 2,000-5,000 kg/h (Tumuluru et al., 2011; Madsen, 2021; Pesliakas, 2021). Commercial and industrial scale machinery systems may include: agglomerators, baggers, boilers, coolers, grinders, shredders and many others. Design features, operating principles and typical applications of some technologies and mechanical systems have been reported by Bajwa et al., 2018; Pradhan et al., 2018; Zhang et al., 2018; Kang et al., 2019; and Šooš, 2021. Machinery for the production of forest chips in Finland has also been reported (Kärhä, 2011). One biomass processing equipment manufacturer claimed to have installations in over sixty countries (Morillas, 2021). Figure 2 presents some devices that are used in briquettes and pellets production.

8. Financial implications

Machinery for briquettes and pellets can appear in various sizes, shapes, and mode of operation (Figure 2). Depending on capacity and level of sophistication (e.g., manual, small scale, automated), equipment costs may range from a few to many thousand dollars. While a recycled container used to manually mold a briquette into the desired shape may cost zero dollars, a shredder could cost € 20,000 (US$ 21,666.67), and a packing or briquetting unit over € 50,000 (US$ 54,166.67) (Pesliakas, 2021). However, the production costs of briquettes and pellets are influenced by feedstock type and pre-processing requirements.

One study in Poland evaluated the quality and cost of small-scale production of briquettes from various biomass feedstocks. The authors reported production cost to range from € 66.55 (US$ 72.10) per tonne for briquetts produced from rape straw, to € 137.87 (US$ 149.36) per tonne for briquettes produced from a 50:50 mixture of rape straw and rapeseed oilcake (Stolarski et al., 2013). In Argentina, the costs of pellet production from sawmill residues were estimated at € 35-47 (US$ 37.92-50.92) per tonne (Uasuf and Becker, 2011).

[A]: Briquette Samples [B]: Pellet Samples

Figure 1. Densified biomasses for green energy production: ([a]. Briquettes; [b]. Pellets) (Bajwa et al., 2018; Hao, 2020; Coad, 2021; Madsen, 2021; Naehrig, 2021; Pesliakas, 2021; Smaliukas, 2021; Šooš, 2021; Ohlson, 2022)

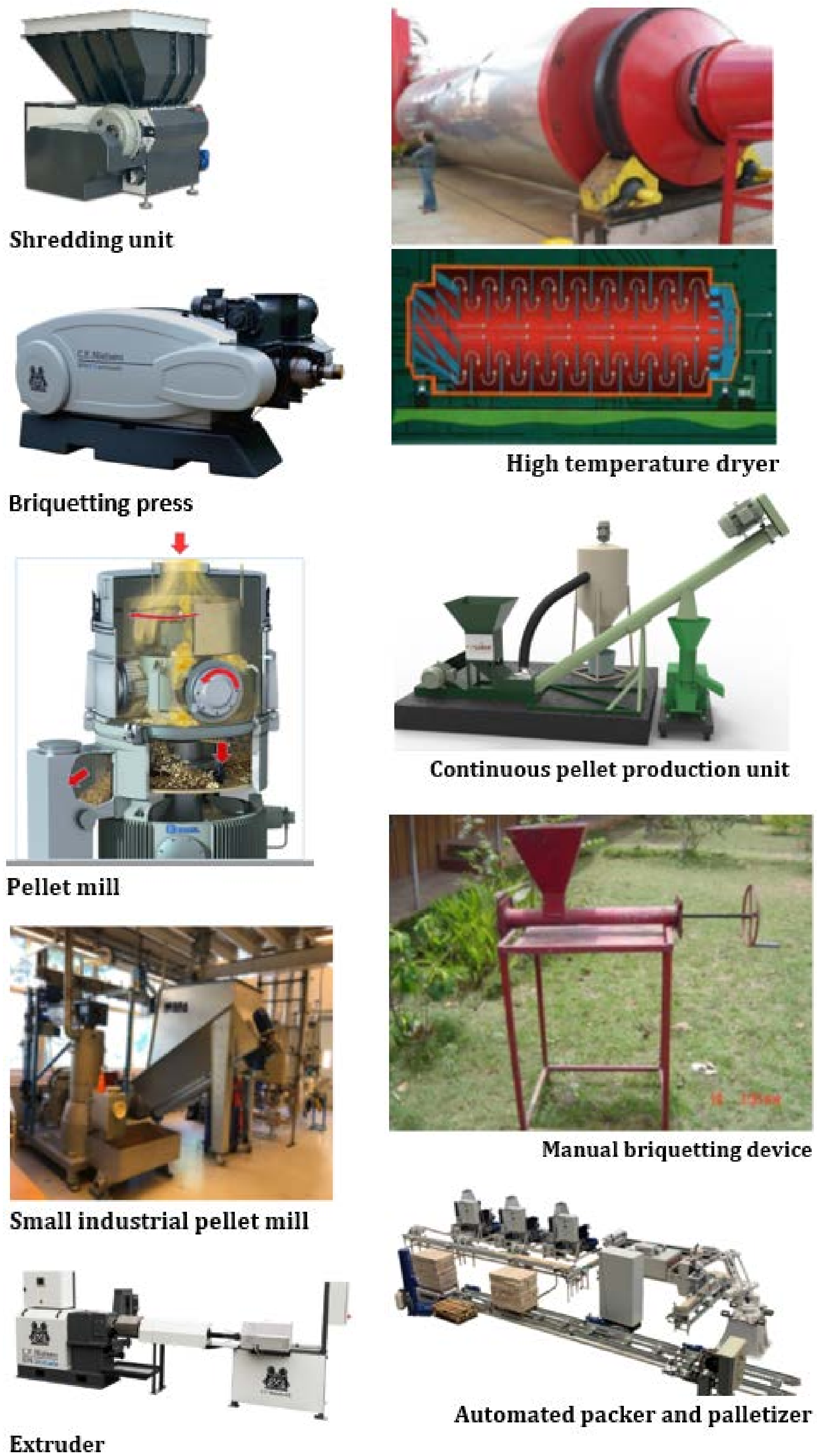

Figure 2. Sample briquette and pellet production machinery systems (Olorunnisola, 2007; Coad, 2021; Madsen, 2021; Naehrig, 2021; Pesliakas, 2021; Kokil, 2022b; Stahl, 2022)

A study in Chile showed that pellet profitability increased by 11.0 % when producing the pellets from olive oil processing wastes and residues (Hernández et al., 2019). In Africa, one study reported that investment cost for large-scale briquette plants vary from US$ 108-350 per tonne, while production costs vary from US$ 61-

237 per tonne. The input cost was estimated to account for 46-54 % of total production cost for large-scale briquette businesses (Asamoah et al., 2016). In the case of Gabon, the investment cost for a 2,000 kg/h pellet equipment operating with the power of 125 kW could range € 50,000-300,000 (US$ 54,166.67-325,000). The production cost for the pellets was estimated at € 65.05 (US$ 70.47) per tonne. For a briquette unit with production capacity of 300-900 kg/h, and energy usage of 25 kW, the investment for equipment was reported at € 5,000-50,000 (US$ 5,416.67-54,166.67) per tonne (Fodor, 2022).

In India, pellets are reported to be sold in local markets at INR (₹) 10 (US$ 0.13) per kilogram (Kokil, 2022b). In Kenya, the cost of kerosene fuel for cooking the traditional meal for a family of five was estimated at Ksh 45 (US$ 0.6). The cost of charcoal briquettes for cooking the same meal was reported to be Ksh 3 (US$ 0.04) (Njenga et al., 2013).

9. Advantages and benefits of briquettes and pellets

Briquettes and pellets exhibit characteristics that enable circumvention of the noted unwanted external costs. Advantages/benefits include convenience, availability, and affordability; mitigation of air pollution, deforestation, soil erosion, health maladies, and global warming occasioned by the harvesting process and combustion products of fossil fuels and traditional biomass. Burning fossil fuels and traditional biomass release air and health-impairing pollutants such as carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons, smoke and other particulate matter. These pollutants may contribute to climate change and premature mortality, as well as cause nausea, sneezing, eye and respiratory irritations, asthma attacks, hospital admissions, and reduced birth weight (Tu et al., 2016).

Production of briquettes and pellets from biomass waste streams minimizes the harvesting of wood (deforestation mitigation), and prevents firewood burning and exposure to combustion products and inherent health maladies. Unlike traditional biomass, briquettes and pellets have a higher energy density, better burning efficiency, maintain consistent quality, and exhibit fewer polluting effects (Pennise et al., 2001; Raymer, 2006; Sjølie, 2012; Muazu et al., 2017; Kokil, 2022a). Unlike fossil fuels, briquettes and pellets feedstocks are available, diverse, renewable, sustainable and environmentally friendly. Briquettes and pellets are regarded as green energy fuels because they could be carbon neutral. There may be no net addition of CO_2 to the environment when the feedstocks are residues and wastes. Replacing charcoal from wood with sawmill residues charcoal briquettes reduced net GHG emissions by 42-84 % (Sjølie, 2012). Pellets produced from olive oil processing wastes (alperujo and orujo) decreased emissions by 78,780 tonnes of CO_2 per year (Hernández et al., 2019). Briquettes and pellets emit less than 20 % of the GHGs typically emitted by fossil fuels (Raymer, 2006). Compared to kerosene fossil fuel, briquette generated lower indoor concentrations of CO_2, CO, and $PM_{2.5}$. The $PM_{2.5}$ emission factor for briquette was also lower than that for kerosene (Njenga et al., 2014). In addition, the net energy savings from densification technologies have been reported in the range: 200-1,000 kJ MJ^{-1}, while GHG emissions savings were reported in the range: 9-50 CO_2-eq (g MJ^{-1}) (Muazu et al., 2017). Table 2 provides more quantitative data on the advantages and benefits of briquettes and pellets.

Table 2
Statistics, advantages and benefits of briquettes and pellets as viable bioenergy technologies to mitigate the adverse effects of traditional biomass and fossil fuels

S/N	Statistics, advantages, benefits	Reference
1	In 2019, about 40.5 million tonnes of wood pellets were produced globally. Europe's share: 55 %; Americas': 30 %; and Asia: 14 %.	WBA, 2021
2	In 2020, approximately (A): 1.93 billion m^3 of wood fuel were produced in the world. Africa and Asia each accounted for 37 %; Americas, 17 %. (B): 53.6 million tonnes of wood charcoal were produced in the world. Africa accounted for 65 %; Americas, 17 %; and Asia, 16.9 %.	WBA, 2021
3	In the USA, the benefit of avoiding health care costs from lead exposure in children was estimated at US$ 110 - 319 billion per year. The impact of reduced particulate matter air pollution was reported to increase overall life expectancy by as much as 15 %	Grosse et al., 2002; Pope et al., 2009
4	In the South Coast Air Basin region of California, USA, the annual economic value of avoiding ozone and PM_{10} pollution effects was estimated at nearly $10 billion	Hall et al., 1992
5	In Grande Porto, Portugal, particulate matter air pollution abatement measures improved air quality by 1 %; reduced PM_{10} emissions by 8 %; and yielded economic benefit of € 8.8 (US$ 10.341) million per year	Silveira et al., 2016
6	In 2011, fossil fuels accounted for 76 % of the energy required for district heating in Lithuania. In 2018, only 31 % of the energy used in district heating emanated from fossil fuels; biomass energy for district heating increased proportionately during this time frame. In 2020, biomass energy accounted for 70 % of the energy required for district heating, and 80 % of requirements for private households. In addition, the price of heating was ≈ 45 % lower due to biomass energy use	Kummamuru, 2021; Gaubyte, 2021

Table 2 continued

Statistics, advantages and benefits of briquettes and pellets as viable bioenergy technologies to mitigate the adverse effects of traditional biomass and fossil fuels

S/N	Statistics, advantages, benefits	Reference
7	The annual cost of production of heat from briquettes for a house in Poland ranged from € 772-986 (US$ 825.104-1053.824). This cost was much lower compared to the cost for the production of equivalent energy from fuel oil, or natural gas, or coal	Stolarski et al., 2016
8	In 2019, about 11.5 million people were employed in the renewable energy sector with bioenergy accounting for ≈ 31 % (3.58 million people)	WBA, 2020; WBA, 2021

10. Conclusion

Because briquettes and pellets could be produced from biomass wastes and residues, they serve as a convenient waste management tool. This also precludes the consumption of fuel wood and associated repercussions (e.g. deforestation). Briquettes and pellets are stable in quality, and have improved energy density and burning efficiency. With their engagement, handling, storage and transport propensity of traditional biomass fuels are dramatically improved. Briquettes and pellets could serve as fuel to produce heat for warmth, boiling water, and cooking food to satisfy domestic needs; generate electricity for small-scale processing operations; fire industrial boilers, gasifiers, and commercial systems to generate heat, or power, or combined heat and power (CHP). However, to improve adoption and market diffusion in low-income economies, public support and interventions (regulatory frameworks, institutional arrangement, technical assistance, resources mobilization, business-friendly policies, credit facilities, investment grants, soft loans, tax incentives, and subsidy schemes) would be needed to offset investment costs and other barriers to their deployment. Utilization devices and systems like cookstoves for low-income rural residents, boilers and gasifiers for small-scale operators and entrepreneurs should be made available, accessible, and affordable. Unlike traditional biomass and fossil fuels, burning briquettes and pellets minimizes harmful combustion products that degrade air quality and impair human health. Since stove type influences emissions of pollutants that degrade indoor air quality, interventions that enable affordable ownership of efficient, safe, and durable cookstoves would alleviate adverse health outcomes. Perhaps the Indian approach (Kokil, 2022a; 2022b) could be modeled.

Traditional biomass is the main source of energy for billions of people in rural communities around the world. And fossil fuels continue to be the predominant energy engine of modern industrial economy. Production of briquettes and pellets from renewable biomass residues and wastes would mitigate hazards associated with traditional biomass and fossil fuels (e.g., climate change, particulate matter air pollution, premature mortality); provide energy security; facilitate rural development; create employment opportunities; boost incomes; and progress poverty alleviation and economic empowerment. Therefore, in the context of circular economy, briquettes and pellets technologies can utilize biomass residues to alleviate poverty, and environment and health constraints; to the benefit of humanity and planet earth.

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Kružna ekonomija primenjena na korišćenje ostataka biomase za smanjivanje siromaštva, očuvanje životne sredine i očuvanje zdravlja

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I Z V O D

Neadekvatno snabdevanje energijom i resursima vode predstavlja ključno ograničenje koje doprinosi siromaštvu i lošim zdravstvenim ishodima u zemljama u razvoju. Zemlje sa niskim prihodima nemaju lak pristup savremenim potrepštinama koa što su struja i voda za piće. S jedne strane, nedostatak električne energije uslovljava oslanjanje na korišćenje tradicionalne biomase kao domaćeg goriva. S druge strane, seča šume za ogrev dovodi do krčenja šuma i degradacije životne sredine. Pored toga, sagorevanje drveta radi toplote prouzrokuje poremećaje ekosistema, tako što se stvaraju toksikanti, nastaje efekat staklene bašte i pojavljuju se štetne čestice. Ovi zagađivači mogu da izazovu zdravstvene probleme, uključujući preranu smrt. Na globalnom nivou, samo zagađenje finim česticama uzrokuje oko 3,3 miliona smrtnih slučajeva godišnje. Ovaj rad pruža uvid u načine na koje bi tehnologije koje primenjuju cirkularnu ekonomiju mogle da pomognu. Posebno je istaknuto korišćenje ostataka biomase i otpada za pravljenje briketa i peleta. Ovi zgusnuti proizvodi od goriva se mogu koristiti kao vid zelene energije u domaćoj i industrijskoj aplikaciji, a samim tim i doprineti smanjenju siromaštva i negativnih ekoloških i zdravstvenih posledica prouzrokovanih korišćenjem tradicionalne biomase.

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Growth Efficiency of Elm Oyster Mushroom (*Hypsizygus ulmarius*) Using Plant - Based Waste Substrates

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ABSTRACT

Mushrooms are nutritionally important organisms that grow well on agricultural plant - based waste substrates. Mushroom cultivation technique is a profitable agribusiness at a small scale. It contains different polysaccharide compounds like cellulose, lignin and hemicelluloses which could be degraded by extracellular enzymes produced by mushroom fungi. Such edible mushrooms have high nutritive values that include proteins, amino acids, carbohydrates, fats, lipids, vitamins and minerals. In the current research, the Elm (*Hypsizygus ulmarius*) mushrooms are cultivated using three different substrates: Paddy straw, corn husk, and a combination of corn husk and paddy straw under aseptic conditions. The spawn running, pin head formation and basidiocarp sprouting time period was faster (14 days) in combined substrates of corn husk and paddy straw compared to the individual substrates. The fruiting body size was larger in corn husk (cap diameter- 7.9 cm, cap length – 5.83 cm) and corn husk + paddy straw substrate (cap diameter- 6.96 cm, cap length – 5.53 cm) than in paddy straw substrate (cap diameter- 6.63 cm, cap length – 4.06 cm). The nutrient composition of the harvested basidiocarps of mushroom from the different substrates had a higher moisture content (69.86 ± 0.41 %) and maximum ash (13.06 ± 0.75 %) content in *Hypsizygus ulmarius* from corn husk + paddy straw substrate. Among these, the protein rich (44.71 ± 0.28 % and 37.88 ± 0.45 %) mushrooms were cultivated using corn husk + paddy straw and corn husk substrate which contained low levels of carbohydrates and optimum levels of fats and lipid content. Thus, corn Husk + paddy straw combination substrate and corn husk substrate were more efficient and suitable for commercial cultivation of *Hypsizygus ulmarius* than the paddy straw substrate.

Hypsizygus ulmarius produces large size basidiocarp and a higher yield than *Pleurotus* species. It is easy to cultivate it with high amount of yield. This commercial edible mushroom production technology is installed in different areas of our environment to enhance and balance the food scarcity in our state to overcome malnutrition. The present study suggested that a combination of corn husk and paddy straw could be used as a substrate for the production of nutritionally efficient mushrooms with a high yield. It would be applicable in various integrated mushroom farming along with agriculture which can lead to an increase in the Indian economy at a certain level.

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1. Introduction

Mushrooms are saprophytic macro fungi with large fruiting bodies. This fungi belongs to both class basidiomycetes and ascomycetes. Mushrooms have been consumed as food since ancient times. In 1991, it was reported that commercial cultivation of mushrooms that belonged to both Ascomycotina and Basidiomycotina families, was about 4.27 million metric tons (Miles and Chang, 1997). About 230 genera and 5,000 species of mushrooms are present. Among these more than 2000 species are edible mushrooms present throughout the world and about 283 species are present in India (Manimaran *et al.,* 2017). Out of the 10,000 known species of mushrooms, 2,000 are safe for humans and about 300 of them possess medicinal properties (Shivashankar and Premkumari, 2014).

Edible mushrooms are highly delicious due its flavor, quality, nutrient value, productivity, and better than other source of plant protein. This has been identified as first-rate food stuff to solve the problem of malnutrition in evolving countries (Eswaran and Ramabadran, 2000). They have been used as food and medicine in India in ancient medical treatise since 3000 BC (Natarajan, 1995). It has medicinal importance as it possess anticancer, antidiabetic, and anti cholesterolenic properties and has an ability to maintain the blood cholesterol at the optimum level preventing cardiovascular diseases (Rai et al., 2005).

The Oyster mushroom is an edible mushroom having good flavour and taste. It belongs to Basidiomycetes-class, Agaricales order and Agaricaceae family. Since mushroom cultivation is a profitable agribusiness that can easily grow as wild in the forests of hilly areas and can be cultivated commercially in temperate and subtropical regions of the world (Shah et al., 2004).

The Oyster mushroom is an efficient lignin-degrading mushroom and can grow well on different types of lingo cellulosic materials. Oyster mushrooms can be grown on various substrate including paddy straw, wheat straw, maize stalks/cobs, vegetable plant residues, bagasse etc. which contain lignocellulose content (Kumar et al., 2019).

The most cultivated edible mushroom is *Lentinus edodes* (about 22 % of the world supply). About 85 % of world's total supply of cultivated edible mushroom is from five genera *Lentinula, Pleurotus, Auricularia, Agaricus,* and *Flammulina* (Royse et al., 2017). *Hypsizygus ulmarius (Bull.),* commonly called as "Elm oyster" or "Blue oyster" is similar to Oyster mushroom, however, they differ in morphology and biological efficiency. It has very large fruiting body, blue-coloured pinheads formed and it becomes light white on maturity, high yield repeatable with meaty flavor and high quality. This new mushroom variety has attractive large shape and flesh has an excellent taste (Sumi and Geetha, 2016).

Many species of mushrooms provide an excellent source of natural compounds that are useful for the treatment of many diseases. Among these mushrooms, *Hypsizygus ulmaris (Bull.)* is used in many purposes due to it is flavor, texture, nutritional content and medicinal properties. Different types of *Hypsizygus ulmarius (Bull.)* extracts have been showing their activity against bacteria, diabetes, inflammation and tumor. It also provides a good source of antioxidants (Al-Faqeeh et al., 2018). The possibility of improving the quality of rice straw substrate by amending it with seaweeds and its influence on substrate biological efficiency (BE), mushroom (*H. ulmarius*) has health-related nutrients and can trace metals contents. The incorporation of 5 % seaweeds resulted in the highest total yield with 22 % higher BE than that of the control and also the highest crude protein concentration in mushrooms. The presence of the highest concentration of trace elements such as Na and K, which are beneficial to human health, was observed (Hausiku et al., 2018).

Hypsizygus ulmarius was first named *Pleurotus ulmarius* and later put under the genus *Hypsizygus* as *Pleurotus* spp. due to white rot and *Hypsizygus* spp. due to brown rot (Volk, 2003). Nutritional study revealed that elm oyster mushroom contains 23.6 % protein, 2.2 % fat, 52.4 % carbohydrates, and 12.9 % fiber on dry weight basis and source of natural antioxidant and antibiotics. (Shivashankar and Premkumari, 2014).

Mycochemical analysis of *Hypsizygus ulmarius* confirmed the presence of compounds such as polysaccharides and phenolic compounds which are responsible for the medicinal properties of such mushrooms. *Hypsizygus ulmarius* (Elm oyster) could be used as a pharmaceutical, medical, and food additive. It is known for anti-tumor, cholesterol controlling and cardiovascular properties (Panavalappil et al., 2016).

The present work was designed to study the effect of different plant-based substrates on the growth of Elm Oyster mushroom. Plant-based wastes containing the cellulose materials such as paddy straw, corn husk, and paddy straw with corn husk could be used as the substrate for the cultivation of elm oyster under household conditions. In this study, the morphological and nutritional status of elm oyster mushroom *(Hypsizygus ulmarius*) derived from the above-mentioned substrates were analyzed under laboratory conditions.

The initial study (preliminary study) dealt with the cultivation of selective elm mushroom (*Hypsizygus ulmarius*) under household condition with the following objectives: study the morphological characterization of Elm Oyster mushroom (Culturing of mushroom under laboratory condition), Mushroom cultivation technology (Sterilization and Preparation of substrate bags, Spawning of substrate, Incubation of spawn inoculated substrate bags under household environment, Harvesting of basidiocarps and its management. The further study was focused to study the nutrient screening of elm mushroom (*Hypsizygus ulmarius*): moisture determination, total ash determination, total fat, total lipid, carbohydrates and estimation of protein. The study of morphology of basidiocarp (fruiting body) of elm oyster mushroom (*Hypsizygus ulmarius*), which included measuring the diameter and length of the cap and stipe and observation of colour of pinhead and basidiocarp, was performed.

2. Materials and Methods

2.1. Preliminary study: Mushroom cultivation technology

2.1.1. Favorable Climatic conditions

Elm mushroom (*Hypsizygus ulmarius*) was grown at temperature ranging from 21 ºC to 30 ºC for a period of 2 to 6 months per year. The winter season is favorable for cultivation.

2.1.2. Sampling

The elm mushroom: *Hypsizygus ulmarius* was selected and the spawn culture (mushroom seed) was collected from Dr. Mohan Mushrooms Research and Training Centre of Madurai.

2.1.3. Cultivation of Mushroom Techniques

2.1.3.1. Pure culture technique

A small inoculam of mushroom seed was cultured on the potato dextrose agar medium and incubated at room temperature for 2-4 days (plate: 1). The grown culture was sub cultured frequently for maintaining and checking the viability of mycelium.

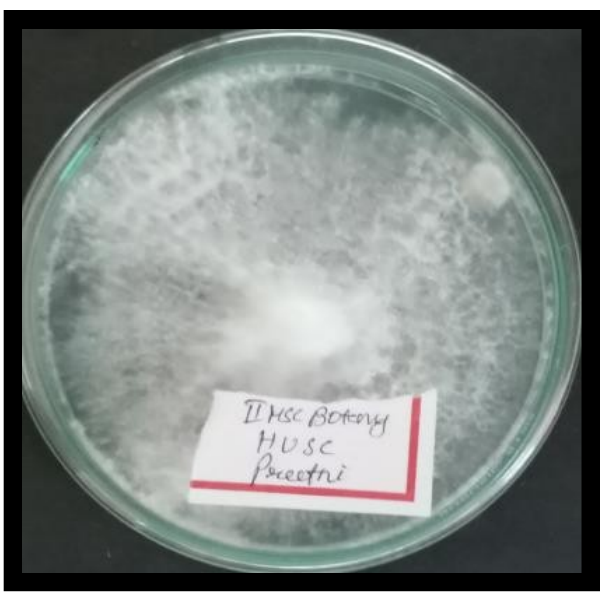

Plate: 1. Elm oyster mushroom (*Hypsizygus ulmarius*) cultured under Microbiological Laboratory condition

2.1.3.2. Substrate preparation

Two different biodegradable substrates namely paddy straw and corn husk were utilized for cultivation of elm mushroom (*Hypsizygus ulmarius*) commercially under controlled condition. Before sterilization, various substrates were water soaked for 14-16 hours. These substrates were sterilized in boiling water at 80 ºC for 30 minutes. After the sterilization, these substrates were dried under shade area to remove excess water (plate: 3).

2.1.3.3. Inoculation of Spawn

The sterilized substrates were packed in a polythene bag with 16 cm length x 9 cm width in size. They were packed as compact layer and formed alternatively by crisscross pattern. Then they were inoculated with spawn culture. Three different bags were packed (paddy straw, corn husk, and combination of paddy straw and corn husk). It was repeated for 4 to 8 layers, it depended upon the size of the bag. The inoculated bags were tied with thick thread and leaving air space above the bag. Such bags were perforated (12-16 holes per bag) with needle for promoting aeration for mycelial growth (plate: 3).

2.1.3.4. Incubation

The prepared mushroom bags were hanged in wooden bench with strings and the wooden bench was moisturized with wet gunny bag and clothes. It was maintained regularly (plate: 4).

2.1.3.4.1. Fruiting

The fully colonized mycelium was observed on the substrate and such condition was ready for the development of basidiocarps. Frequent spraying of water over the bags in the incubating place depending upon the atmospheric condition. The cultivation place was provided with sufficient ventilation during fruiting body formation (Plate: 5-7).

2.1.3.4.2. Fruiting body protection

The mushroom fruiting body was protected from mites, flies and other microbial diseases by regular monitoring and removing contaminated bags.

2.1.3.5. Fruiting body harvesting and maintenance

The harvesting of basidiocarp was done based on the size and shape of the fruit body by hand picking. They were harvested before spore release and it was done for three times/bag.

Fresh mushrooms were packed in perforated poly-bags and stored at low temperature (4 ºC) for 4 to 5 days.

2.2. Secondary study

2.2.1. Moisture content determination (Raghuramulu et al., 2003)

The moisture content of the harvested sample was determined by measuring the weight before and after. And water content was evaporation (plate: 10).

Percentage of moisture = (Initial fresh weight - final weight) x 100 /weight of sample

2.2.2. Total Ash content determination (AOAC, 1990)

Three grams of mushroom was taken heated in a hot air oven at 170 ºC for 30 min and cooled (Plate:10). Ash content was calculated using the formula:

Ash content (g/100g sample) = Weight of ash/weight of sample taken x 100

2.2.3. Total Fat content determination (AOAC, 1990)

Ten grams of mushroom was weighed and extracted with petroleum ether for 16 hours. The extract was dried, cooled and measured (plate: 11). The percentage of fat was determined using the formula:

Percentage of fat = 100(Weight of Soxhlet flask with extract fat – Weight of empty Soxhlet flask)/Weight of sample

2.2.4. Total Lipid determination (Folch et al., 1957)

The 5 g of mushroom sample was suspended in fifty milliliter of 2:1 chloroform: methanol mixture then mixed well and left for 3 days. It was filtrated and centrifuged at 3,000 rpm in centrifuge. The methanol upper layer was removed by micropipette and the chloroform was made to evaporate in a hot air oven. The remaining dried sample was measured as crude lipid (plate: 11).

2.2.5. Protein Estimation (Lowry et al., 1951)

Five grams of mushroom were weighed and ground with water with the help of a pestle and motor. Then it was filtered using a muslin cloth. The filtrate was collected in a centrifuge tube and centrifuged for 5 minutes at 3,000 rpm. The supernatant was collected and pellet was discarded. The collected supernatant was treated by adding equal volume of 10 % Trichloro acetic acid solution. Then it was again centrifuged at 3,000 rpm for 5 minutes. The supernatants were discarded. The collected pellets were taken and dissolved in 15 ml of 0.1 N of sodium hydroxide solution. It was then centrifuged again. The supernatant was taken and made up to 20 ml with 0.1 N of sodium hydroxide solutions. This was taken as the test solution. 1 ml of the test solution and 5 ml of alkaline reagent was added and allowed to stand for 10-15 minutes in a dark place. After that 0.5 ml of folinphenol reagent was added to it. The optical density of the solution was measured at 660 nano meter by using the UV-Visible spectrophotometer (plate: 11). Bovine serum albumin was used as a standard for calculating the protein content of the sample.

2.2.6. Carbohydrate determination

The carbohydrate content of the harvested mushroom was calculated by the formula:

The percentage of carbohydrate = (100 - total protein + total ash + total lipid + total fat)

2.2.7. Measurement of the size of cap and stipe

The size of the cap and stipe of the fruiting body was measured by a meter scale and expressed in terms of cm. Both length and diameter of cap and stipe were measured.

2.2.8. Colour of pinhead and basidiocarp

The color of the pinhead and basidiocarp of each bag was noted.

2.2.9. Data analysis

The measured data collected in the study have subjected to mean descriptive statistics.

3. Result and discussion

Mushrooms lack chlorophyll and are non-green organisms. They have extensive enzymes which degrade lignocellulosic materials for their nutrition and growth. Different mushrooms have different lignocellulolytic enzymes (cellulases, ligninases, endoglucanases and cellobio hydrolases) profile required for substrate bioconversion (Buswell and Chang, 1994; and Buswell et al., 1996).

Mushrooms are a good source of protein, vitamins and minerals and are known to have a broad range of uses, both as food and medicine. A high nutritional value of oyster mushrooms has been reported with protein (25-50 %), fat (2-5 %), sugars (17-47 %), mycocellulose (7-38 %) and minerals (potassium, phosphorus, calcium, sodium) of about 8-12 % (Syed et al., 2009). More than 3,000 mushrooms are said to be “the main edible species” of which only ten of those are used in industrial purpose. Its global economic value is nevertheless now staggering and an initial reason for the increase in consumption is the combination of their food value as well as their medicinal values. A variety of mushroom species constitute cost-effective food-stuff for both supplementing the nutrition to human kinds (Chang and

Miles, 2004) and other purposes.

Chang and Buswell (1996) reported the extractables derived from either the mushroom mycelium or fruiting body which are known as nutraceuticals. There are a very important for the expanding mushroom biotechnology industry. It has been shown that constant intake of either mushrooms or mushroom nutraceuticals (dietary supplements) can make people fitter and healthier. In addition, mushroom cultivation can also help to convert agricultural and forest wastes into the useful matter and reduce pollution in the environment. Therefore, this technique of mushroom cultivation could make three important contributions to society: production of healthy food, manufacture of nutraceuticals and reduction of environmental pollution.

The improvement and development of modern technologies, such as computerized control, automated mushroom harvesting, preparation of compost, production of mushrooms in a non-composted substrate, and new methods of substrate sterilization and spawn preparation, will increase the productivity of mushroom culture. All these aspects are crucial for the production of mushrooms with better flavor, appearance, texture, nutritional qualities, and medicinal properties at low cost (Sánchez, 2004).

Chang (2007) reported that many mushrooms possess a range of metabolites of intense interest to pharmaceutical e.g. antitumour, immunomodulatory, antigenotoxic, antioxidant, anti-inflammatory, hypo cholesterolaemic, antihypertensive, antiplatelet aggregating, antihyper glycemic, antimicrobial and antiviral activities (antitumour, immunomodulation agents, and hypocholesterolemia agents and food (ex: flavor compound) industries. The above data demonstrated there are 660 species from 182 genera of mushrooms containing antitumor or immune stimulating polysaccharides. The wild mushroom species contain higher contents of protein and lower fat concentrations than commercial mushroom species. But commercial species have higher concentrations of sugars, while wild sp. contained lower values of MUFA but also higher contents of PUFA. There were no differences between the antimicrobial properties of wild and commercial species (Barros et al., 2008).

Mushrooms degrade lignin cellulosic substrates and can be produced on natural waste materials from agriculture, woodland, animal husbandry and manufacturing industries (Rinker, 2002). Many people consumed mushrooms as comestibles for their nutritional value and folk medicine for their supposed medicinal importance. Besides their excellent flavour mushrooms have attracted much attention due to their proven healthy properties (Chiron and Michelot, 2005).

The preliminary study focused on the pure culture of mushroom seed (spawn) which was initially collected from Dr. Mohan Mushrooms Research and Training Centre, Madurai, and was sub-cultured in potato dextrose agar medium under an aseptic condition in the microbiology laboratory. After 3-4 days of incubation, white cottony mycelium was grown on the potato dextrose agar plate (Plate: 1). In the present study, massive growth of mycelium observed in all the *Hypsizygus ulmarius* spawn inoculated substrates (Paddy straw, corn husk, corn husk + paddy straw) within 4 to 6 days (Plate: 2). The pin head formation (Plate: 2) occurred at various time interval viz. Paddy straw in 19 ± 1.0 days, Corn husk in 17± 1.0 days and Corn husk + Paddy straw in 13 ± 1.0 days. Favorable climatic condition determined the fruiting body formation in the above-mentioned substrates. But the fruiting body sprouting was observed on the 20th day in Paddy straw bag, on the 19th day in Corn husk, and on the 14th day in Corn husk + Paddy straw (Table 1 and Plate: 2). This result indicated that the mycelium colonization, pin head formation and fruiting body development in all plant-based substrates depended upon the environment factors and composition of substrates used for cultivation and it might be optimum for the edible elm mushroom: *Hypsizygus ulmarius*. The harvested mushrooms from each substrate were collected in polythene covers aseptically and were stored in a refrigerator for further analysis work.

The cultural studies of *Hypsizygus ulmarius* revealed that out of nine media tested, MEA and WEA media supported maximum (90 mm) growth followed by PDA medium. Optimum temperature was 25 °C and pH level was 7 for the mycelial growth of the fungus. There was gradual decline in growth of fungus when temperature and pH level increased or decreased (Kushwaha et al., 2011). But the other study showed (Jonathan et al., 2012) that the cultivation of *Pleurotus ostreatus* on different agricultural wastes such as *Oryza sativa* straw, *Gossypium hirsutum* wastes and *Milicia excels* sawdust with the addition of *Oryza sativa* bran additive to enhance the mycelial growth. *Gossypium hirsutum* substrate with rice bran additive showed high moisture content (93.43 %), crude protein (28.02 %), fat contents (8.72 %) and fiber contents (17.42 %) of *P. ostreatus*.

Fan et al. (2008) observed that mushroom production could convert the huge lignocellulosic waste materials into a wide diversity of products (edible or medicinal food, feed and fertilizers), protecting and regenerating the environment. And also, mushroom production could generate equitable economic growth which already had an impact at national and regional levels. This impact was expected to continue increasing and expanding in the future, because more than 70 % of agricultural and forest materials are nonproductive and have been wasted in the agro-industrial processing or even consuming period.

The present investigation reported that the morphology study of *Hypsizygus ulmarius* was determined by measuring the diameter, length of cap and stipe of the fruiting body (Basidiocarp) and colour of pinhead and Basidiocarp.

Corn husk + paddy straw **Paddy straw** **Corn husk**

Plate: 2. Elm oyster's mushroom (*Hypsizygus ulmarius*) spawn running process and basidiocarp formation stage

Table 1
Effect of different substrate on the growth of elm oyster mushroom (*Hypsizygus ulmarius*)

Sl. no	Substrate	Spawn running (Days)	Pin head formation (Days)	Basidiocarp formation (Days)
1.	Paddy straw	6.3 ± 1.5	19 ± 1.0	20.6 ± 1.5
2.	Corn husk	5 ± 1.0	17 ± 1.0	19.6 ± 1.5
3.	Corn husk and paddy straw	4 ± 1.0	13 ± 1.0	14.6 ± 1.5

Values are mean of three replicates ± SD

The Diameter and length of cap and stipe of basidiocarp from the Paddy straw substrate bag was 6.63 ± 0.66 cm; 4.06 ± 0.23 cm; 1.23 ± 0.11 cm; 3.86 ± 0.35 cm, from corn husk substrate bag was 7.9 ± 3.5cm; 5.83 ± 2.36 cm; 1.06 ± 0.11cm; 4.36 ± 1.01 cm and from corn husk + paddy straw substrate bag was 6.96 ± 3.10 cm; 5.53 ± 1.70 cm; 1.6 ± 0.55 cm, 3.36 ± 0.90 cm (Table 2). The colour of pinhead and basidiocarp of elm oyster mushroom from three substrate bag was also observed and noted. The colour of the pinhead and basidiocarp of

H. ulmarius in a corn husk, Corn husk + paddy straw and paddy straw substrate bag was observed to be same colour. The colour of the pinhead of *H. ulmarius* was greyish blue in colour. At maturity, the colour was gradually changed into light white colour from greyish blue colour. The colour of basidiocarp of *H. ulmarius* was white in colour.

Buah et al. (2010) investigated the cultivation of *Pleurotus ostreatus* on various substrates (corn cob and sawdust). There were different steps involved in the cultivation methods like composting the substrates, bagging the substrates, sterilizing the bagged compost, spawning, incubation and cropping. The result showed that the corn cob used as a substrate for oyster mushroom cultivation performed better than saw dust in terms of the growth and yield of the mushroom. The Corn cob could therefore substitute the saw dust since it is cheap and available during a year, unlike sawdust, where the demand is between mushroom growers and poultry farmers.

The investigation (Pokhrel et al., 2016) on the growth of oyster mushrooms in easily available substrates such as corn cob, vegetable residue and waste paper was examined with the supplementation of rice bran and chicken manure separately. The observation showed that best mycelial extension, early pin head formation and better yield in corn cob substrate followed by paper waste and vegetable residue. Among these substrates used, corn cob showed the highest yield with range from 99.08 to 109.50 % biological efficiency, whereas 69.81 to 88.36 % and 52.26 to 65.22 % biological efficiency was observed in paper waste and vegetable residue respectively.

Sumi and Geetha (2016) analyzed the morphological study on *Hypsizygus ulmarius* showed that the sporocarps were medium to large having a dark blue colour in the pinhead stage which became creamy white on maturity with an irregularly shaped, convex pileus with gills attached to the stem, but not decurrent and cylindrical, smooth and eccentric stipe and their studies on developmental morphology showed that *H. ulmarius* took an average of five days from the day of pinhead formation to complete maturity. When compared with *Pleurotus florida*, *H. ulmarius* took more time (18 days) for complete spawn run in paddy grains and the yield was higher on paddy straw (1.096 g/kg) than *P. florida* (976 g/kg). Nutritional studies showed that *H. ulmarius* contained an appreciable amount of carbohydrate (29 %), protein (32 %), and fiber (17.69 %).

Munna et al., (2019) reported that Banana leaves substrates in combination proved to be best for the cultivation of *Hypsizygus ulmarius*. Cultivation of elm oyster mushroom on combination with paddy straw and different substrates were investigated. According to this study, the minimum time taken for a complete mycelium run (19.33 days) was in T3 (wheat straw + banana leaves) and maximum time was observed in T6 (wheat straw + doob grass) (23.16 days). Minimum time from the primordial stage to the harvesting stage was recorded in T3 (wheat straw + banana leaves) (25.83 days) and maximum time was recorded in T6 (wheat straw + doob grass) (27.33 days). A higher yield was obtained in T3 (wheat straw + banana leaves) (936.6 g) with the highest biological efficiency (93.66 %). Maximum protein content was recorded in T3 (wheat straw + banana leaves) (35 %) and maximum carbohydrate in T3 (wheat straw + banana leaves) (25.33 %).

The growth and biomass of *Hypsizygus ulmarius* were studied based on different media, temperatures, light duration, pH level and Relative humidity. Among the tested media potato dextrose agar medium was found most suitable medium for the growth (89.00 mm) and biomass (fresh mycelium weight: 13.93 gm and dry mycelium weight 0.57 gm) of *H. ulmarius*. The optimum temperature required 26 °C was most suitable. Maximum relative humidity for radial growth was observed at 75 % relative humidity. Complete darkness or zero hours of light was excellent for mycelial growth and biomass of *H. ulmarius*. Maximum growth of *H. ulmarius* was obtained at pH 8.0 on potato dextrose agar medium (Baghel et al., 2019).

Khade et al. (2019) reported that the addition of organic and inorganic supplements to the substrate increase the yield of elm oyster mushroom. The study reported that the yield performance varied due to different treatments like neem cake at 2 % produced maximum yield of mushroom (841.11 g/kg dry) substrate followed by treatment, maize flour at 2 % with a yield of 831.11 g/kg dry substrate, whereas the lowest yield of 320 g/kg dry substrate was recorded in treatment soybean flour at 2 %. A significant variation in average fruit body weight (2.72 to 10.64 g per fruit), pileus diameter (4.09 to 6.72 cm), stipe length (2.62 to 4.43 cm), and stipe size (2.73 to 3.84 cm) were noted due to different treatments.

Kumar et al. (2019) conducted a study on the cultivation of *Hypsizygus ulmarius* mushroom on the different substrate such as banana leaves, casuarina needle, coir pith, ground nut shell, paddy straw, sugarcane trash, sugarcane bagasse, saw dust and water hyacinth and supplements on the sporophore production. Paddy straw (489.6 g/bed) was most efficient in enhancing the yield of *H. ulmarius* and Followed by water hyacinth (474.4 g/bed) and sugarcane trash (472.7 g/bed).

Cyriacus et al. (2020) investigated the cultivation and yield performance of *Hypsizygus ulmarius* grown on agricultural waste from *Musa sapientum* (MS), *M. paradisiaca* (MP), *M. accuminata* (MA), MS+MP, MS+MA, MP+MA, MS+MP+MA. Such a result showed that MS+MA had the shortest fruiting time of 12 days while MP, MP+MA had the longest, which was 14 days. The largest capsize was obtained in MP while the smallest capsize was in MA. The longest stipe length was produced by MS+MP while MS+MA has the shortest

Table 2
Morphological study of fruiting body (basidiocarp) of elm oyster mushroom (*Hypsizygus ulmarius*) from different substrates

Sl. no	Substrate	Cap diameter (cm)	Cap length (cm)	Stipe diameter (cm)	Stipe length (cm)
1.	Paddy straw	6.63 ± 0.66	4.06 ± 0.23	1.23 ± 0.11	3.86 ± 0.35
2.	Corn husk	7.9 ± 3.5	5.83 ± 2.36	1.06 ± 0.11	4.36 ± 1.01
3 .	Corn husk and paddy straw	6.96 ± 3.10	5.53 ± 1.70	1.6 ± 0.55	3.36 ± 0.90

Values are mean of three replicates ± SD

stipe. MP+MA substrates gave the highest biological yield while the least was recorded by MS+MA. Biological Efficiency was best at 76.58 % produced by MP+MA and lowest at 56.48 % by MS+MA.

In the secondary investigation, the nutrient analysis of the harvested *Hypsizygus ulmarius* was done and measured data were tabulated (Table 3). According to this the moisture content was maximum (69.86 ± 0.41 %) in corn husk + paddy straw substrate when compared to other substrates (66.06 ± 0.70 % in paddy straw; 61.66 ± 0.50 % in Corn husk) (Table 3). The ash content of the harvested basidiocarps of *Hypsizygus ulmarius* (Table 3) from Corn husk + Paddy straw substrate showed maximum at 13.03 ± 0.75 % and it was the least level in a Corn husk (6.33 ± 0.29 %) when compared to paddy straw substrate (8.20 ± 0.40 %). Shivashankar and Premkumari (2014) analyzed the total ash content, water-soluble extractive value, alcohol soluble extractive value and moisture content of *Hypsizygus ulmarius*. Qualitative phytochemical screening was also studied that showed the presence of alkaloids, phenolics, saponins, tannins, glycosides, carbohydrates and proteins. Usha and Suguna (2015) analyzed that two strains of *H. ulmarius* CO_2 and *H. ulmarius* IIHR revealed that the protein, carbohydrate and fiber contents were high. Lipid content in two strains of *H. ulmarius* ranged from 3.65 to 5.35 % and fat content ranged from 3.55 to 4.80 %, respectively.

Sethi et al. (2012) experimentally showed that cultivation of the *Hypsizygus ulmarius* in three different substrates [wheat straw, paddy straw and wheat straw: paddy straw (1:1)] was pretreated with hot water (80 ºC) and chemicals such as caebendazim and formaldehyde. Among these wheat straw pretreated with hot water (80 ºC) showed maximum biological efficiency, least spawn run period and pin head appearance in 27-33 days. Mishra et al. (2013) evaluated the total phenolics, radical scavenging activity (RSA) on DPPH, ascorbic acid content and chelating activity on Fe^{2+} of *Pleurotus citrinopileatus*, *Pleurotus djamor*, *Pleurotus eryngii*, *Pleurotus flabellatus*, *Pleurotus florida*,*Pleurotus ostreatus*, *Pleurotus sajor-caju* and *Hypsizygus ulmarius*. Agglomerative hierarchical clustering analysis on basis of seven parameters revealed that studied mushroom species fall into two clusters; Cluster I included *P. djamor*, *P.eryngii* and *P. flabellatus*, while Cluster II included *H. ulmarius*, *P. sajor-caju*, *P. citrinopileatus*, *P. ostreatus* and *P. florida*.

Sadhana and Sivakumar (2020) previously analyzed the different biodegradable substrates such as newspaper waste, coir waste, ground nut shell coat waste and paddy straw for the comparative cultivation technique of *Pleurotus ostreatus* mushroom. They reported that the nutrient values of all the harvested basidiocarps of mushrooms derived from the various substrates have been determined the higher protein content noted in both newspaper wastes (51.93^{b} ± 3.066 % and ground nut shell (43.06^{ab} ± 6.025 %) wastes substrates. The results showed that the edible mushrooms could be cultivated by using biodegradable wastes from different sources and this technology was applied in small-scale industry for the production of efficient *Pleurotus* species for our health at low cost.

Mushrooms have been treated as a special kind of functional food during ancient times but in recent decades they are known as "the ultimate health food" because of their unique nutritional status. Based on in this view, many mushrooms have been reported to have rich nutritional value with high content of proteins, minerals, fibres, trace elements and low/ no cholesterol (Breene, 1990). The carbohydrate content of mushrooms represents the bulk of fruiting bodies counting for 50 - 65 % on dry weight basis. They contain low fat and oil content (Barros et al., 2008) compared to that of proteins and carbohydrates.

In the present study, the lipid content of harvested *Hypsizygus ulmarius* was measured the lowest at 0.20 ± 0.02 % in corn husk + paddy straw and high lipid content in Paddy straw substrate-based mushroom was 0.38 ± 0.02 %. The lipid content of the *H. ulmarius* from Corn husk substrate showed an approximate level as 0.29 ± 0.02 % (Table 3). The protein content of harvested *Hypsizygus ulmarius* was maximum at 44.71 ± 0.28 % in Corn straw + paddy straw and 37.88 ± 0.45 % in Corn husk substrate and it was minimum in (17.41 ± 0.22 %) paddy straw substrate (Table 3). But minimum fat content was measured at 10.03 ± 3.51 % in Corn husk + paddy straw substrate and maximum was observed at 26.20 ± 3.06 % in Paddy straw substrate. But the fat content (Table 3) of the *Hypsizygus ulmarius* from Corn husk showed approximate level (21.50 ± 5.56 %). When compared to others substrates, the carbohydrate content of elm oyster mushrooms (Table 3) was higher at 47.81 ± 0.20 from paddy straw substrate and approximately same level of carbohydrate content from both corn husk substrate and Paddy straw substrate at 34.00 ± 1.05 % and 32.00 ± 0.50 %. This variation in nutritional level of *Hypsizygus ulmarius* derived from different plant based substrates determined by the energy sources like

Table 3
Effect of different substrates on the moisture content (%) and nutritional content of elm oyster mushroom (*Hypsizygus ulmarius)*

Sl. No	Substrate	Moisture content (%)	Ash Content (%)	Lipid Content (%)	Protein content (%)	Fat content (%)	Carbohydrate content (%)
1.	Paddy straw	66.06 ± 0.70	8.20 ± 0.40	0.38 ± 0.02	17.41±0.22	26.20 ± 3.06	47.81±0.20
2.	Corn husk	61.66 ± 0.50	6.33 ± 0.29	0.29 ± 0.02	37.88±0.45	21.50 ± 5.56	34.00±1.05
3.	Corn husk and paddy straw	69.86 ± 0.41	13.06 ± 0.75	0.20 ± 0.02	44.71±0.28	10.03 ± 3.51	32.00±0.50

Values are mean of three replicates ± SD

cellulose, lignocellulosic, hemicelluloses and pectinoses rich substrate within it. This study concluded that *Hypsizygus ulmarius* utilized the plant-based waste substrate for their metabolic processes and produced massive mycelium over the substrate along with sprouting of basidiocarp within a short period of growth. A similar study was reported by Biswas and Kuiry (2013). It showed minimum spawn period, maximum size of sporophores, maximum yield and biological efficiency in *Hypsizygus ulmarius* when compared with *Pleurotus* species such as *Pleurotus florida*, *Pleurotus sajor-caju*, *Pleurotus ostreatus* and *Pleurotus flabellatus*.

A recent study (Sen et al., 2020) evaluated the effect of nutritional medium, temperature and colour on mycelial growth behavior of *Hypsizygus ulmarius* in vitro. According to this study dense and white mycelium was grown on potato dextrose agar (PDA) medium and it required least days for full growth (10.50 days) followed by Malt Extract Medium (11.25 days). Out of different colour polythene wrapping, black colour polythene treatment gave the best result as it required the least days for spawn run (16 days) followed by blue colour (16.25 days) which provided uniform growth of the medium.

Totally three substrates were analyzed for the present study. Among these substrates the combination of corn husk and paddy straw substrates was appropriate for *Hypsizygus ulmarius* cultivation technique when compared to other utilized substrates. The nutrient composition was fractionally resolute the distribution of different level components at significant percentage for each substrate applied in this study. The plant-based waste substrates applied in this work comprised different energy sources like cellulosic, lignocellulosic and hemicellulosic compounds which could be utilized by the selective mushroom fungi for the growth and metabolic activities. The present work confirmed that the protein content was higher and low level of lipids, fats and carbohydrates in such selective elm oyster mushroom grown on plant- based waste substrate which could be suggested to include this mushroom in regular dietary food for diabetes and other ill patients.

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Efikasnost rasta gljive *Hypsizygus ulmarius* u prisustvu biljnih otpadnih supstrata

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I Z V O D

Uzgoj gljiva, koje predstavlju nutritivno važne organizme koji imaju uspešan rast na otpadnim supstratima poljoprivrednih biljaka, jeste profitabilan agrobiznis. Pečurke sadrže različita polisaharidna jedinjenja, kao što su celuloza, lignin i hemiceluloza, koja se mogu razgraditi u prisustvu ekstracelularnih enzima koje gljive proizvode. Takve jestive pečurke imaju visoku hranljivu vrednost i sadrže proteine, aminokiseline, ugljene hidrate, masti, lipide, vitamine i minerale. U ovom eksperimentu, pečurke *Hypsizygus ulmarius* su uzgajane na tri različita supstrata: slami, kukuruznoj ljusci i kombinaciji ova dva supstrata pod strogo kontrolisanim uslovima. Period razvijanja, formiranje klobuka i nicanje su bili brži (14 dana) na kombinovanom supstratu od slame i kukuruzne ljuske. Veličina plodišta je bila veća na suspstratu od kukuruzne ljuske (prečnik klobuka – 7,9 cm; dužina kape – 5,83 cm) i na kombinovanom supstratu (prečnik klobuka – 6,96 cm; dužina kape – 5,53 cm) u poređenju sa onim na supstratu od slame (prečnik klobuka – 6,63 cm; dužina kape – 4,06 cm). Hranljivi sastav ubranih pečuraka sa različitih supstrata je imao najveći sadržaj vlage (69,86 ± 0,41 %) i maksimalni sadržaj pepela (13,06 ± 0,75 %) kod *Hypsizygus ulmarius* sa kombinovanog supstarta. Ove pečurke su takođe bile bogate proteinima (44,71 ± 0,28 % i 37,88 ± 0,45 %), sadržale su niske nivoe ugljenih hidrata, kao i optimalne nivoe masti i lipida. Dakle, kombinovani supstrat i supstrat od ljuske kukuruza su bili efikasniji i pogodniji za komercijalnu kultivaciju *Hypsizygus ulmarius* od supstrata slame.
Hypsizygus ulmarius ima veći klobuk i daje veći prinos od vrste *Pleurotus.* Lako ga je uzgajati i imati visok prinos. Ova komercijalna tehnologija proizvodnje jestivih gljiva je primenjena u različitim oblastima kako bi se poboljšala i uravnotežila ishrana u Indiji, a isto tako i prevazišao problem neuhranjenosti. Ovaj rad sugeriše da bi se kombinacija kukuruzne ljuske i slame kao supstrata mogla koristiti za proizvodnju nutritivno efikasnih pečuraka sa visokim prinosom. Mogao bi da se upotrebi kod uzgoja pečuraka i tako doprineti povećanju ekonomije na određenom nivou.

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Construction Biotechnology: The Promise of Sustainable Buildings

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A B S T R A C T

The construction industry is one of the thriving industries in the world. There are various modern techniques implemented and latest construction materials are used to build an eco-friendly and sustainable building. Construction Biotechnology is a new scientific and engineering discipline that has been developing exponentially during the last decade. In this biotechnology-based construction, microbially treated construction materials are used. The bio-agents used in construction biotechnologies are pure or enriched with cultures of native microorganisms or microorganisms isolated and activated from the soil. Overall process of construction is also different due to involvement of biotechnology-derived processes and technologies. Biotechnology-based construction has shown potential of cost-effectiveness which renders such construction technologies promising in the current era. Architects, engineers, and people involved with construction are suggesting these biotechnology-based construction technologies for eco-friendliness and high sustainability of these novel construction materials. As a field, biotechnology offers countless solutions to common environmental problems well beyond the construction industry.

1. Introduction

Biological technologies are one of the main global directions of technological and scientific progress, providing a breakthrough in obtaining new materials with unique properties, through integrated use of diverse fields such as biochemistry, microbiology, and engineering sciences to provide the possibility of technological (industrial) application of microorganisms (Vasanthabharathi, 2017). Materials obtained through biotechnology have a high innovative potential and by now are already in demand in many industries, including construction. Biotechnology began to find application in many technological processes for obtaining building materials - preliminary processing of raw materials, production of adhesives, bio-surfactants for construction purposes, etc. (Plank, 2004; Achal, 2015; Salahudeen et al., 2018; Barberan et al., 2020).

The construction industry is a major contributor to the current model of unsustainable development due to its huge environmental impacts. The world produced 4.3 billion metric tons of cement in 2014, and this production will continue to increase due to construction demand in the world (Barberan et al., 2020). To help reduce those maintenance costs and make buildings and bridges safer, researchers are now offering concrete with the power to heal itself. In addition to economic constrains, cement and steel manufacturing are among the most environmentally harmful processes in the construction sector, accounting for 37.2 % of manufacturing primary energy demand and nearly 50 % of carbon dioxide emissions.

The field of biotechnology and also the field of biomimetics show a great potential in offering innovative

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solutions that can contribute to a greater eco-efficiency of the construction industry (Stabnikov et al., 2015). The use of microorganisms such as bacteria, fungi, or algae is studied to improve the properties of conventional materials such as concrete; in the creation of new construction materials with similar characteristics to existing materials (Barberan et al., 2020). Production process of novel construction materials are more sustainable and some of these microorganisms can be incorporated into newly developed construction systems as well (Pacheco-Torgal et al., 2013).

The use of construction biomaterials is one of these new, friendly, and sustainable alternatives since the raw material used is mostly from renewable biological resources, e.g. agricultural biomass residues and, recently, waste microorganisms which resulted from other industries have gained popularity for its production (Barberan et al., 2020).

2. Biotechnology

Biotechnology is a scientific discipline and an area of engineering on industrial manufacturing and practical applications of microorganisms and their products such as proteins, nucleic acids, polysaccharides, storage compounds, and low molecular weight metabolites (Ivanov et al., 2015). This area of study has already been successfully applied in sectors such as health, agriculture, and the industrial segment as well. Biotechnology is technology that uses living organisms, biological systems or their derivatives to create or modify products and processes (Erickson et al., 2012). Biotechnology can help to solve major global problems caused by the operations of the engineering and civil construction market - especially with regard to the reduction of environmental impacts caused by construction processes (Ivanov and Stabnikov, 2017).

After three centuries of industrialization, human beings see themselves in the overwhelming need to seek potential in natural systems. This potential in the area of construction currently translates into the creation of new bio-inspired materials, which mix biological and engineering processes within a research area called biotechnology (Barberan et al., 2020).

In addition, through the development of advanced materials that offer more strength and durability and better value for money, biotechnology must also drive efficiency and financial results in our market. Food, Medical, Veterinary, Agricultural, and Environmental Biotechnologies differ in their areas of applications. A new biotechnological discipline, Construction Biotechnology, has appeared during the last decade (Ivanov et al., 2015; Ivanov and Stabnikov, 2017).

3. Construction biotechnology

By definition, construction Biotechnology refers to the newly emerged interdisciplinary field incorporating diverse applications of environmental microbiology, industrial microbiology, and biotechnology in civil engineering. Construction biotechnology designates the development of construction processes mediated by microorganisms and the use of biotechnological techniques for the production of construction materials (Barberan et al., 2020; Chen et al., 2020). The high potential to generate a positive impact on this market, both from an economic and sustainability point of view, makes research with construction biotechnology very promising. The main benefits of biotechnology in the engineering and construction market are related to the creation of more efficient, smart, sustainable, and cheaper materials (Kroll, 1990; Ghosh et al., 2006; Achal et al., 2011; Pilla, 2011; Jian et al., 2012).

New materials are already being developed using living organisms. The search for greater resistance, with greater efficiency and durability and lower cost, is the main objective. Some are in the experimental phase, such as mortars capable of regeneration and insulation that change shape according to humidity, controlling the internal climate of a building (Jonkers et al., 2016).

This modern science successfully combines the application of scientific knowledge about engineering methods for the production of construction biomaterials, as well as the use of bioprocesses in the construction industry (Barberan et al., 2020).

Construction Microbial Biotechnology is a new area of science and engineering that includes microbially-mediated construction processes and microbial production of construction materials. Low cost, sustainable, and environmentally-friendly microbial cements, grouts, polysaccharides, and bioplastics are useful in construction and geotechnical engineering. Construction-related biotechnologies are based on activity of different microorganisms: urease-producing, acidogenic, halophilic, alkaliphilic, denitrifying, iron- and sulfate-reducing bacteria, cyanobacteria, algae, and microscopic fungi. The bio-related materials and processes can be used for the bioaggregation, soil biogrouting and bioclogging, biocementation, biodesaturation of water-satured soil, bioencapsulation of soft clay, biocoating, and biorepair of the concrete surface (Table 1). Construction Microbial Biotechnology is progressing toward commercial products and large-scale applications. The biotechnologically produced materials and construction-related microbial biotechnologies have a lot of advantages over conventional construction materials and processes (Ivanov et al., 2015).

Researchers proposes three possible directions of application of biotechnologies to the construction industry: (1) work with 100 % organic material with thermal insulation functionality and structural qualities, (2) the use of micro luminescent micro-organisms for the design of devices with the ability to emit light without electricity consumption, and (3) cementation of granular structures mediating the use of environmentally friendly bacterial populations, without toxicity or corrosion (Barberan et al., 2020).

Development of materials and construction systems requires the study of microorganisms such as bacteria, fungi or algae, in the improvement of properties of conventional materials such as concrete; in the creation of new construction materials with similar characteristics to existing materials, with the advantage that their production processes are more sustainable; and in the incorporation of some of these microorganisms into new construction systems, which in addition to providing an aesthetic component, develop an energy task in the form of biomass (Barberan et al., 2020).

4. Applications of biotechnology in construction

Taking into account the process of gradual deterioration of our planet, alternatives that allow balancing this process produced mainly by the hand of man should be considered so, in this work we propose, as an alternative, to familiarize the scientific community with the application of biotechnological tools in the Cement industry that includes the use of microorganisms and their potential characteristics (Stabnikov and Ivanov, 2016; Barberan et al., 2020).

Different biotechnological products and biotechnologies applied to civil engineering are being developed in that direction (Figure 1). The reduction of the environmental impact of the conventional production of construction materials, together with a decrease in production costs, use of waste in secondary processes, increased quality and useful life of the materials obtained are considered in the process. These issues, among others, constitute the main advantages of this technology. In the following section, some novel applications of construction biotechnology has been highlighted (Figure 1) (Barberan et al., 2020).

Table 1
Applications of biotechnology in construction

Product	Microbial source	Function	Ref.
Sodium gluconate	*Gluconobacter oxydans* *Aspergillus niger* *Aureobasidium pullulans*	Set retarder; plasticizer; corrosion inhibitor used in concrete	Ma et al., 2015
Xanthan gum	*Xanthmonas campestris*	Thickener and set retarder for self-consolidated concrete	Plank, 2004
Welan gum	*Alcaligenes sp.*	Thickener, set retarder for self-consolidated concrete	Pacheco-Torgal and Jalali, 2011
Scleroglucan	*Sclerotium, Corticium, Sclerotinia, Stromatinia*	Thermostable thickener	Pacheco-Torgal et al., 2012
Succinoglycan	*Alcaligenes sp.*	High shear-thinner with temperature-induced viscosity	Ma et al., 2015
Curdlan gum	*Agrobacterium sp.; Alcaligenes sp.*	Thickener; self-consolidated concrete	Plank, 2003
Sodium alginate	*brown seaweeds*	Stabilizer, thickener, and emulsifier	Fytili and Zabaniotou, 2008
Bacterial cell walls	*Aerobic bacteria*	Microstructured filler for concrete	Pei et al., 2013
Carrageenan	*red seaweeds*	Foam for protecting freshly poured concrete from premature drying during highway construction	Mun, 2007
Dextran	*lactic acid bacteria*	Admixture to Portland cement, self-levelling grouts, fresh or saltwater oil well cement slurries, and micro-fine cements improving flow resistance	Pacheco-Torgal and Jalali, 2011
Pullulan	*Aureobasidium pullulans*	Thickener; self-consolidated concrete	Pacheco-Torgal and Labrincha, 2013
Self-healing concrete (ureolytic process)	*Bacillus megaterium* *Deleya halophila* *Halomonas euryhaline*	Re-inforced concrete; self-healing concrete; bio-cement	Talaiekhozan et al., 2014
Self-healing concrete (silica process)	*Leuconostoc mesenteroides*	Re-inforced concrete; self-healing concrete; bio-cement	Talaiekhozan et al., 2014
Microbe induced $CaCO_3$ precipitate (MICP)	*Bacillus pseudofirmus* *Sporosarcina pasteurii*	Re-inforced concrete; self-healing concrete; bio-cement	Barberan et al., 2020
Biobrick	*Synecococcus sp.*	Re-inforced eco-friendly brick	Khitab et al., 2016
Bioinsulator	*Ganoderma lucidum* *Pleurotus ostreatus*	Low cost insulator; foam sealing	Barberan et al., 2020

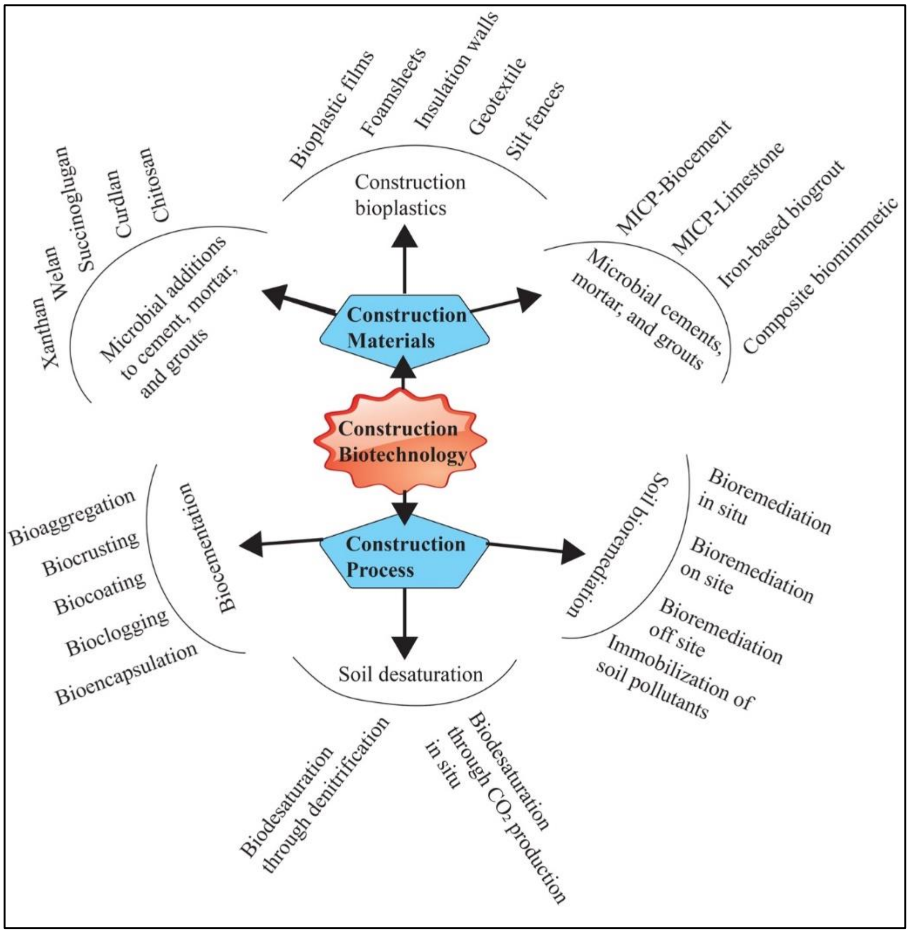

Figure 1. Potential applications of construction biotechnology

4.1. Bio-Brick

Brick is an essential component of any construction. About 40 % of the cost of a masonry brick is in the fuel used to burn the kiln. In addition to costing money, the burning necessary for the production of traditional bricks also contributes to the increase in the emission of polluting gases. Bio-crick was developed from a by-product generated by microorganisms, which binds sand particles together, creating a material similar to corals and strong enough to be used in homes (Dhami et al., 2012). In this biotechnology proce**ss,** bacteria creates natural cement in just five days**,** without using fossil fuels (Brown et al., 2004; Bernard et al., 2014).

New bricks, according to their developers, are highly stable and have a long service life, durability. This building material, in accordance with the technology of its production, can be made, or more precisely, "grown" from ordinary sand, using calcium chloride, common bacteria and carbamide, that is, urea. This, according to the developers, is an optimal, affordable and practically complete modern alternative to the technology of firing building bricks, which is currently practiced by many enterprises, and requires the use of a significant amount of energy resources.

4.2. Bio-Insulator

Currently, civil construction mainly uses materials of petrochemical origin to insulate homes and buildings. The most used materials are derived from plastics, and such plastic materials can take hundreds of years to decompose. Bio-insulator has emerged as a sustainable alternative of such plastic based insulators (Binici et al., 2016). Bio-insulator has been developed from materials made from fungi, as well as from agricultural waste such as plant stems and seed husks. The fungus grows in a mold or inside a cavity in walls, providing rigid structural insulation for homes. The resulting insulation is fire resistant and fully compostable material (Chang et al., 2015).

Fungal mycelium is light and resistant, and since it can be produced on different substrates, the properties are highly variable and manageable. Its density is in a range of 0.05 to 0.59 g/cm, and although wood is more resistant, its tensile strength value is very high (it varies between 20 and 240 MPa) when compared with triplex, whose tensile strength is 0.55 g/cm^3 and polystyrene is 34 MPa (Girometta et al., 2019). The mycelium has also been studied for its high capacity for thermal and acoustic insulation. Other characteristics are: it floats, it is fire retardant, a dielectric insulator, and highly moldable. The material has very low thermal conductivity, which makes it an ideal thermal insulator. This characteristics, added to its fire retardant, resistance and low density properties, allow it to become a perfect candidate to replace plastic packaging foams as insulator (Latif et al., 2014; Velasco et al., 2014).

4.3. Bio-Concrete

Concrete is one of the most widely used materials in the world in the construction industry that uses 1.6 billion tons of cement, and each ton of cement emits 1 ton of CO_2 into the atmosphere in its manufacture (Wu et al., 2012; Wang et al., 2012; Barberan et al., 2020). It is considered to be the mostly used building material on Earth. The annual production of Portland cement concrete reaches about 10 km^3/year, most of which is used in the execution of reinforced concrete structures (Stocks-Fischer et al., 1999; Jonkers et al., 2010; Pacheco-Torgal and Labrincha, 2013). With the help of biotechnology, Bio-Concrete has been developed with bacteria (such as *Bacillus pseudofirmus*) that, in contact with water, generates calcium carbonate which fills cracks and holes in the structure. Thus, it makes possible to build a building capable of repairing itself each time it suffers damage such as a crack that occurs in the concrete structure (Reddy et al., 2010; Van Tittelboom et al., 2010). How it works is simple: the contact of water with the cracks in concrete activates the spores so that they begin to feed on another aggregated substance, calcium lactate, producing calcite crystals. In this way, when the cracks are still microscopic, they can be filled with repair material, avoiding wear and tear and pathologies (Reddy et al., 2012; Kalhori and Bagherpour, 2017). Precipitation of polymorphic iron-aluminium-silicate ((Fe_5AI_3) $(SiAl)O_{l0}(OH)_5$) and calcium carbonate ($CaCO_3$) are the most important processes used for designing the biological self-healing concretes. *Bacillus pasteurii* and *Bacillus sphaericus* family are the most common microorganisms used in designing self-healing concrete through ureolytic processes (Toohey et al., 2007; Wang et al., 2012; Wu et al., 2012). The bacteria *Leuconostoc mesenteroides* plays an important role in precipitating the silica for development of self-healing concrete (Talaiekhozan et al., 2014).

4.4. Bio-Cement

Cement is widely used as a construction material (Stabnikov et al. 2013). However, its production generates environmental impacts during all manufacturing stages. Added to this fact, world cement production is responsible for consuming about 10-15 % of total industrial energy and 5-8 % of anthropogenic CO_2 emissions (Uson et al., 2013; González-Kunz et al., 2017). Bio-cement is an alternative to cement (De Muynck et al., 2010) that can produce binder materials through MICP treatment to improve the strength and durability of cementitious materials (Phillips et al., 2013; Dhami et al., 2014). “Biocement” is a MICP product that aims to reduce or eliminate spaces between particles of a granular material (sand as an aggregate, for example). As cement production is largely responsible for the high carbon emissions in the civil construction segment, the use of any alternative such as Bio-Cement will help to make buildings more sustainable. Scientists have found that carrot and beet fibers can make cement stronger, more economical and more sustainable (Ariyanti et al., 2012). The “nanoplatelets” extracted from vegetables increase the amount of calcium silicate hydrate, responsible for the structural performance in concrete. As a result, stronger concrete that uses less cement is generated. In addition, vegetables also improve the quality of the final product by reducing the number of cracks that appear in the concrete (Wu et al., 2012; Sarayu et al., 2014). Microorganisms most commonly associated with bio-cement production through MICP process include *Bacillus pseudofirmus*, *Sporosarcina pasteurii* and *Shewanella* sp. (Dhami et al. 2014; González-Kunz et al. 2017). Additional research is needed to improve production technology and reduce undesirable by-products to allow the use of MICP on a commercial scale.

5. Future perspective

The commercial and residential construction sector represents 39 % of the CO_2 emitted into the atmosphere, generating 30 % of solid waste and 20 % of water pollution. Based on the previous data, it can be concluded that half of the CO_2 expelled into the atmosphere is related to the construction of buildings throughout all its phases: construction, use, and subsequent demolition. Therefore, the construction sector and its CO_2 emission, as a threat of climate change, must be considered. Therefore, to reduce the environmental impact on the construction sector, it is essential to use materials that do not require the use of fossil fuels and cause high carbon emissions (Barberan et al., 2020).

The use of biologically based products has increased at a steady pace in the last decade. It is estimated that by 2020 the global market based on bioproducts will reach $ 250 billion and that by 2030 a third of the produced materials will come from biological resources. This study raises the possibility of implementing bio-cements and bio-concrete and its possible application in several areas where there is a higher demand for construction (Barberan et al., 2020).

The planet faces environmental challenges that require an urgent response to assure a sustainable development and the needs of future generations. Researchers around the world have been working in recent years on developing biotechnological solutions to problems in different areas, including construction. Living organisms are already being applied in the creation of more resistant materials, mortars capable of regeneration and insulation that changes shape according to humidity, controlling the building's internal climate. These are applications that can help solve major problems caused by processes in this segment, such as the large generation of waste. Better economic results for the sector with less environmental impact will be the main benefits of construction biotechnology to the market. The application of bacteria, fungi and plants in the manufacturing process of building materials will not only generate differentiated physical elements, but will also bring buildings closer to the dynamics of biology.

Novel biomaterials offer several advantages over the traditional construction materials: (1) biomaterials give us the opportunity to capture properties from nature and exploit them for more sustainable construction; (2) the advantage of the microstructure of construction biomaterials is its simplicity and ease of manufacture; (3) the new biomaterials could contribute to the drastic reduction of the environmental impact in construction; (4) bio-construction materials are equivalent to a reduction in waste and optimal recycling and waste from other sectors is reused for the manufacture of construction biomaterials; and (5) its cost is low and its ecological impact of its use is also low.

Most of this research is still in the experimental phase. But some studies have already achieved promising results. A part of these possibilities has been commercially exploited by companies in the construction industry. In a few years, therefore, the use of biotechnological solutions in the sector will be an increasingly significant reality throughout the world. Keeping up with the great global movements will help you be more prepared for the changes that should revolutionize processes in the engineering and construction market in the coming years.

The gathering of these contributions and cutting-edge research in the targeted areas, specifies the needs for significant changes related to education, research and public policy, in order to plan a sustainable future of the construction industry with the associated benefits related to the eco-efficiency.

6. Conclusion

We are living in the fourth industrial revolution. This new era is marked by the fusion of different technologies and the union of digital, physical, and biological spheres. Because of all this, biotechnology is gaining more and more importance and space. And this area of science can generate a great sustainable and economic impact on the civil construction market. After all, new materials and processes arise precisely because of biotechnology. Microbe-derived construction related applications are limitless and useful in applications that aim to generate safe and environmentally stable products. Even though construction biotechnology has its advantages, further studies are needed to overcome its limitations before commercialization on an industrial scale.

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Biotehnologija u građevinskoj industriji: budućnost održivih zgrada

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I Z V O D

Građevinska industrija je jedna od naprednijih industrija u svetu. U njoj se primenjuju različite moderne tehnike i najnoviji građevinski materijali koji se koriste za izgradnju ekološki prihvatljivih i održivih zgrada. Biotehnologija u građevinskoj industriji je nova naučna i inženjerska disciplina koja se postepeno razvijala tokom poslednje decenije. U ovoj biotehnološkoj disciplini koriste se građevinski materijali tretirani mikrobima. Bioagensi koji se koriste u građevinskim biotehnologijama su čisti ili obogaćeni kulturama izvornih mikroorganizama ili mikroorganizmima koji su izolovani iz tla i aktivirani. Celokupni proces izgradnje je takođe drugačiji zbog upotrebe postupaka i tehnologija zasnovanih na biotehnologiji. Ovakav način izgradnje se pokazao kao potencijalno isplativ, što biotehnologije čini obećavajućim. Arhitekte, inženjeri i ljudi uključeni u izgradnju predlažu ove biotehnologije kao ekološki prihvatljive i visoko održive. Biotehnologija kao oblast nudi bezbroj rešenja za česte probleme u vezi sa ekologijom, ne samo u okviru građevinske industrije.

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Establishment of Deposit Refund System in Greece for PET bottles: Economic Analysis, Benefits and Impacts

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ABSTRACT

The current paper deals with the implementation of the Deposit Refund System (DRS), as new recycling system in Greece for PET packages, in accordance with the European Directive 2019/904. The main purpose of this work was the presentation of a cost-benefit analysis that evaluated the suggestions and the impacts of the aforementioned European Directive for Greece. In addition to the cost-benefit analysis, a comparison between the DRS and the existing recycling model for PET (PolyEthylene Terephthalate) packages was carried out aiming at eliciting the ramifications for Greece. Furthermore, a mathematical model was set up, based on data regarding PET recycling in Greece. This model describes the operation of the corresponding DRS in Greece, and could be useful for understanding, establishing, and improving DRSs for other waste commodities.

1. Introduction

The idea of deposit-refund was generated long time ago to cope with the problem of the increasing purchase power of society and the concomitant increase of recyclable waste littering. Several studies, mostly theoretical, have been carried out on various issues of DRSs and their comparison with other recycling systems (Bohm, 1981; Palmer and Walls, 1997). The application of DRS on the recycling of beverage packages has been proved the most popular (Lavee, 2010; Linderhof et al., 2019; Guangli et al., 2020) but it can be applied on various waste commodities as well, such as lead batteries (Gupt and Sahay, 2015), tires (Walls, 2013), motor oil (Schmitz et al., 2012), electronics (Zhong and Zhao, 2012), etc. (OECD, 2015). The current paper deals with the investigation of the prerequisites, economics, benefits, and impacts from the establishment of a DRS for PET bottles in Greece.

The global production of plastics has risen from 2 million metric tons in 1950 to about 400 million tons nowadays and, according to estimations, it will be doubled by 2035, as shown in Figure 1 that has been generated by the authors from data obtained from World Economic Forum (2016) and World Wide Fund for Nature (2019). In Greece, 730,000 tons are annually produced, which denotes that every Greek citizen discards approximately 68 kg of plastic per year (Dalberg Advisors, 2019).

According to Plastics Europe, association of plastic manufactures (2016), the majority of global production of plastics is lined up for packaging and beverages, which are the main sources of plastic waste because of their limited lifetime. Figure 2, which is based on data from D' Amato et al. (2019), shows the share of plastic consumption in various industrial sectors.

Furthermore, PET (PolyEthylene Terephthalate) is vastly used for the production of food packages and beverages. It is a clear lightweight plastic manufactured from ethylene glycol and terephthalic acid, which are

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combined in order to form the polymer chain. Additionally, PET is extruded, cooled and finally cut into pellets. Afterwards, these pellets are liquefied through heating and then molded in order to provide a product of desired shape (Plastics Europe Association of Plastic Manufactures, 2018).

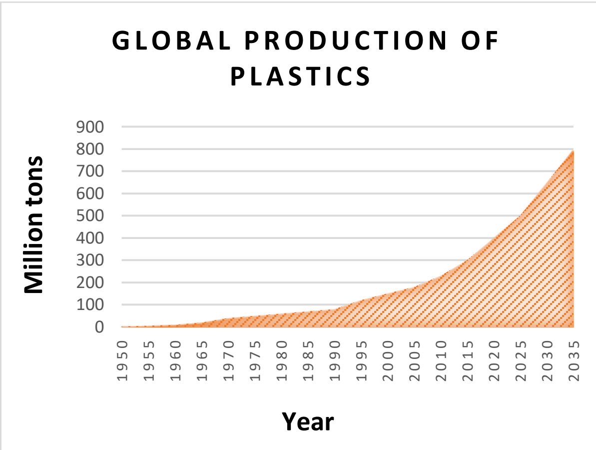

Figure 1. Annual growth rate of global production of plastics since 1950 (World Economic Forum, 2016; World Wide Fund for Nature, 2019)

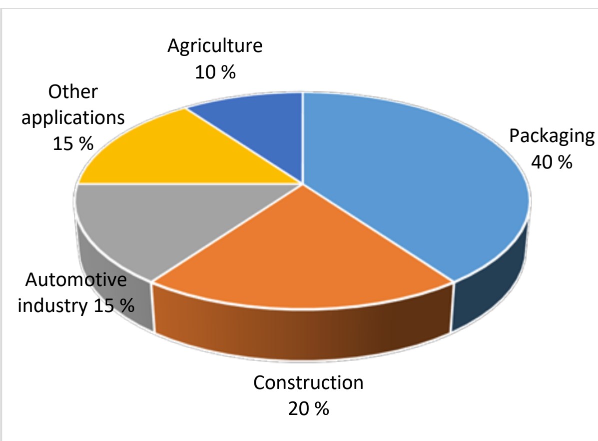

Figure 2. Global application of plastics (D’ Amato et al., 2019)

PET is completely recyclable and it is the most recycled plastic worldwide. After washing and collecting the PET containers through the recycling system, PET can be re-melted or chemically broken down into its components in order to make new PET resin, which can be reused for new containers (Plastics Europe, 2016). Although recycling is the most sufficient way to manage the bailed PET packages, some PET bottles can be found in landfills.

Every year, 5-13 million tons of plastic end up in oceans. Consequently, the plastic waste is transported to the shore through the ocean currents, causing many financial and environmental problems (Jambeck et al., 2015). Plastic waste from European States ends up on its coast, especially in the countries around Mediterranean Sea, thus suppressing tourism and fishery activities of the local communities. Additionally, PET packages can be disintegrated into microplastics which are harmful for ecosystems. Microplastics are polymers with size less than 5 mm, which can be easily ingested by marine fauna causing health problems (Razis and Christopoulos, 2021).

In view of the foregoing, the European Union and, by extension, the Greek Government incorporated the European Directive 2019/904 in order to reduce the pollution caused by plastic containers. This Directive sets the target of 77 % for the return rate of plastic beverages by 2025 and the detailed description of plastic beverage items is provided in the Directive as well. Moreover, the target increases to 90 % by 2029. To achieve these high return-rate targets, the Greek Government ought to establish and operate a Deposit Refund System (DRS), which is responsible to collect the plastic beverages and other materials if needed (Razis and Christopoulos 2021). It is expected that the establishment of DRS in most EU States will be a key factor in promoting Circular Economy. Higher recycling rates combined with better design of plastic containers will boost the market of recycled plastics and, simultaneously, reduce the pollution from plastics, especially in the Mediterranean Sea. The operation of DRS in various European States showed that its establishment achieved high return rates, with concomitant reduction of plastic littering (Table 1).

Table 1
Return rates from various European DRSs (created by the authors with data from: Hogg et al., 2015; CM Consulting, 2016; Fullana-i-Palmer et al., 2017; Drab and Sluciakova, 2018)

European Deposit Refund System	Return rate (%)
Croatia	90
Denmark	89
Estonia	90
Finland	92
Germany	98
Iceland	87
Lithuania	74
Netherlands	95
Norway	95.4
Sweden	82.7

Even though the DRS is an effective recycling system to drastically achieve high return rates, recycling should not be displayed as the sole and sufficient solution to approach the circular economy. As it is already shown, the plastic production is drastically growing; as a result, recycling will not be able to handle the quantities of plastic in the future. Considering that the price of virgin PET, produced by oil, is lower than that of recycled PET and the great investment of the petrochemical industry, it is obvious that recycling and Circular Economy will be undermined even if global return rates of recycling systems remain high as shown in Table 1. To recapitulate, achieving high return rates and promoting recycling are not sufficient means to ensure environmental sustainability; on the contrary, promoting recycling without taking control of global plastic production will lead to greater problems because recycling will be degraded to a reason for greater production and, therefore, pollution.

The main purpose of the current paper was to present an integrated technical and financial investigation for the establishment of a DRS in Greece for PET bottles and to compare it with the existing Extended Producer's Responsibility (EPR) model. In addition, a mathematical model was set up, which was useful for understanding and improving the operation of the DRS. The rest of the paper is organized as follows. Section 2 describes the function of a DRS and the relationship between deposit merit and return rate. Section 3 presents in details various economic parameters, which are very important to evaluate the establishment of a DRS in Greece for PET bottles. The effects and benefits of the DRS are presented in section 4 followed by the conclusions in section 5.

2. Theoretical Presentation of the Deposit Refund System and Methodology

2.1. Describing the function of the Deposit Refund System

The Deposit Refund System (DRS) is an efficient means through which the Governments could encourage citizens to retrieve the recyclable packages. The system imposes a deposit, which is included in the price of the product and can be returned to the consumer in case of retrieving the package undamaged. This is the main reason that DRS can achieve the highest return rate in comparison with Extended Producer's Responsibility system (EPR), which is widely used in many European States (Fullana-i-Palmer et al., 2017). The route of material and deposit is presented in Figure 3.

The Deposit System Management Operation (DSMO) is responsible for the productive function of the whole deposit refund system. The income of DSMO consists of:

- Deposits
- Producers' Fee that is a capital paid by producers to contribute to the recycling system
- Revenues from selling retrieved packages to recyclers.

As far as the outgoings, the following components are concerned:

- Retail handling fee, a capital paid to indemnify the retailers who take part in the system
- Operating costs of the DRS
- Deposits for the retrieved packages to indemnify the consumers.

2.2. Setting the merit of a deposit

The merit of the deposit is a very important factor to establish a DRS, since it defines the funds to be attributed to DSMO as income, part of which is used afterwards to compensate the consumers. It is easily understandable that the rate of the deposit designates the return rates of the system. A higher rate provides the consumers with a bigger motivation to return their recyclable packages (Biala and Aregbeyen, 2018). However, the level of the deposit should always keep up with the average salary of the Member State, where the DRS will be introduced. Otherwise, the citizens experience a price increase of the product, with concomitant result the fall of their purchasing power. Figure 4 presents the function between the value of the deposit, which is the domain of the function, and the return rates for some established European deposit systems.

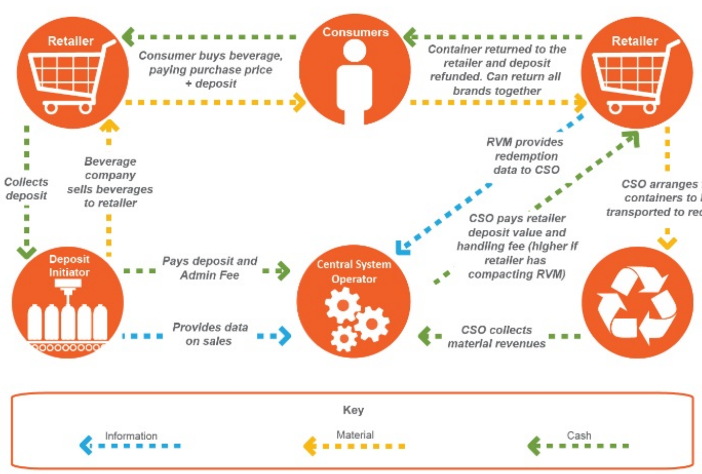

Figure 3. The route of material and deposit through industry, retailer, consumer and final recycler (Cordle et al., 2019; after permission)

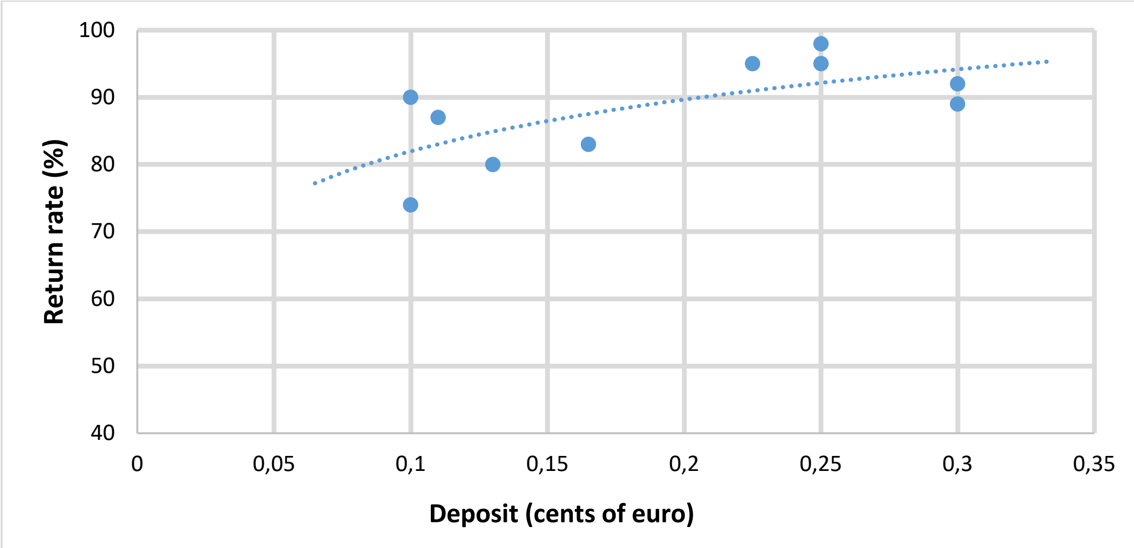

Figure 4. Return rate as a function of deposit value (The data for the creation of this diagramby the authors have been obtained from CM Consulting, 2016)

Obviously, the fluctuation of the return rate for the DRS of a specific-waste is affected by many factors such as the effectiveness of the financial study, on which the DRS was established, and the income of citizens. However, Figure 4 provides considerable information for the valuation of the deposit. In most cases, the choice of value 20 - 40 cents leads to high return rate, over 90 %. On the other hand, a value of 10 - 20 cents results in lower return rates, typically 74 – 87 %. Furthermore, it should always be noted that a DRS, working with high return rate (for example 95 %), demands quite more funding to operate in comparison with lower return rates (such as 90 %). As a result, the difference of 5 cents in the merit of the deposit induces different return rates and, by extension, greater operating costs. The correlation between the return rate and the operating cost will be distinct in the next sections. In view of the aforementioned, the value of 15 cents seems suitable for the needs of the DRS in Greece.

The methodology of the other economic parameters is presented in the corresponding Section.

3. Results and Discussion

3.1. Revenues and working capital

In Greece, 50 thousand tons of PET per year (throughout the study metric tons are considered only, 1 metric ton=1,000 kg) are imported and converted into packages of 0.5 and 1.5 liter. By assuming that the aforementioned packages participate in 1:1 ratio and with corresponding package weight of 20 and 30 g, it derives that approximately 2 billion packages of PET per year are discarded and, consequently, included in the DRS. Can-packages may also be included in the DRS but this is currently under consideration from the side of the Greek State. This work focuses on PET packages only. With 2 billion packages, which represent 50 thousand tons of PET, the annual total deposit capital that is handled among industry, retailers, DSMO and consumers, is estimated to about 300 million euros. It must be pointed out that the Greek DRS presents a distinctiveness in comparison with the other European DRSs regarding the distribution of the working capital throughout the year. In Greece, the consumption of beverages (both in cans and PET packages) is increased drastically in summer compared to winter because of tourism. As a result, the percentage of the annual total deposit capital for summer months is higher in comparison to the working capital for the wintertime.

- The monthly working capital in summertime, namely the percentage of the annual total deposit capital from May until September, is about 2.5 times higher than the corresponding in wintertime because of the increased consumption and, by extension, the increased retrieve of packages. The DSMO should be able to afford the working capital to pay the retailers for the deposits of the committed packages to the system. In case that the deposit refund system in Greece starts operating in summer, the DSMO will need 39 million euros monthly as summer working capital, which corresponds to approximately 13 % of the annual total deposit capital.
- On the other hand, the monthly working capital of the non-tourist season, from October until April, amounts to 15 million euros, which is 5 % of the annual total deposit capital.

Considering a deposit of 15 cents, the DRS in Greece is expected to reach a return rate of 85 % according to Figure 4. As a result, the outgoings for the DSMO to indemnify the consumers for the claimed deposits are amounted to 255 million euros. So, the annual earnings from unclaimed deposits are estimated at 45 million euros (or 3.75 million euros per month) as follows:

0.85 · 2 billion PET = 1.7 billion packages of PET returned to DRS

0.15 · 1.7 billion PET = 255 million euros

300 million euros – 255 million euros = 45 million euros annual earnings from unclaimed deposits

Considering an average price for PET of 310 euros per ton, the annual earnings from selling the packages to recyclers are estimated at:

0.85 · 50,000 tons PET = 42,500 tons PET recovered through the DRS or

310 euros/ton · 42,500 tons ≈ 13 million euros

To recapitulate, the annual earnings from unclaimed deposits and packages selling will be 58 million euros.

By comparing the two sources of earnings, it is comprehensible that the DRS is more profitable, if the system degrades its primary target and performs a lower return rate, as the income from unclaimed deposits is 3.5 times higher than the corresponding from returned packages sale. All these occur because the deposit value is higher than the price of bailed PET beverages. This is the main reason that the DSMO should operate as non-profit organization and should always be under close State control. In case that DSMO functioned with profit orientation, the management operation should decrease its return rate and utterly undermine the environmental purpose.

3.2. Investment and operating cost

The main factor that determines the total investment cost of a DRS is the number of reverse vending machines (RVM). Even though the current analysis takes into account only PET packages, the RVMs should be able to collect more materials to efficiently meet the requirements for future needs. Deposit Refund is a system with high investment cost; hence, the Greek State should reap as many benefits as possible from DRS.

The proportion of residents per RVM is an index that can provide an approach of the total RVMs needed for a country. However, this index must be carefully considered because:

- There is not integrated experience, as most European DRSs are still under development
- The proportion of residents per RVM is an index that uses data regarding the general population of the State and the total number of RVMs. Consequently, other significant factors, such as population density, extension of urban centers, etc., are not counted in.

For example, the Danish DRS operates approximately 3,200 RVMs for 5.8 million residents or 1,813 residents per RVM. Nonetheless, the population density of Denmark, with land area of 43 thousands square kilometers, is 135 residents per km^2 contrary to the population density of Greece that is 82.

Another important factor is the transportation cost of retrieved material, which is increased for Greece because of the geographical features. Especially during summer times, the transportation from Greek islands is quite expensive because of the massive consumption caused by tourists. In case of DRS, the transportation of intact, uncompressed material from islands would be unbearable for the DSMO. On account of this, the DSMO should invest more capital to buy even more RVMs to be placed on islands. So, the retrieved material will be cut, compressed, weighted and ready for its transportation. An additional tactic to avoid the rise of transportation cost is the cooperation of the DSMO with local recycling and sorting facilities so that the packages to be cut and compressed, even if they have not been collected through RVM. It is estimated that approximately 6,000 RVMs are required for the operation of the DRS in Greece, which is noticeably higher than in other countries with similar population and consumption. However, this is a strategic decision that every DSMO has to make; for Greece, the higher investment cost for more RVMs will result in the restriction of the annual cost of transportation, which is very significant.

A higher number of RVMs implies that the majority of empty packages will be collected automatically. The correlation between the number of packages collected automatically through RVM and the total number of packages collected through DRS is expressed by the rate of automation R, which is defined in the following way (Drab and Sluciakova, 2018):

R = 100 · (number of packages collected through RVM) / (total number of packages collected through the DRS system)

For Greece, the system is expected to operate at a rate of 90 %. The investment cost in this case is estimated to be around 155 million euros. This amount corresponds to the cost for:

a) investment, installation, and maintenance of RVMs,
b) processing the empty packages, which are not collected automatically, and
c) setting up the DSMO.

In order to reduce the total cost for the establishment of

DRS, the DSMO should take advantage of the existing transportation network and stations of trans-shipment. Similarly, the DSMO should use the existing facilities, which operate under EPR system, to process the empty packages instead of establishing new ones.

Having approached the investment cost, the next factor that should be calculated is the operating cost. The operating cost of a DRS consists of two main sectors:

- The expenses that are related to retailers.
- The outgoings that are related to the different processes and DRS has to perform.

The first sector is referred to the capital, which is paid by DSMO to indemnify the retailers who participate in the project. This capital is called Retail Handling Fee (RHF) and reimburses the retailers for the costs of collecting and storing empty packages. As a result, RHF depends on the way of collection (automatic or manual). For the collection through RVM, the compensation is higher. The main factors that determine the level of compensation are:

- The area of the shop that is reserved for the collection. In the case of automatic collection, this area is reserved by the RVM.
- The bags, which are used for the storage of retrieved packages.
- The consumption of energy (kWh) for the RVMs operation.
- The labor costs. Both automatic and manual collection need workers to operate. In fact, in many European countries, the increase of the working responsibilities does not necessarily imply corresponding rise of the salary; as a consequence, part of the compensation is converted into income for the employer. However, even in this scenario, a DRS analysis should consider the additional labor costs.

Table 2 presents a reimbursement price per empty package for the European Deposit Systems.

Table 2
Reimbursement price per retrieved PET package for the European DRSs (created by the authors with data obtained from: CM Consulting, 2016; Cordle et al., 2019)

Country	Euro per package for RVM and manual collection	
Croatia	0.02 (RVM)	0.01 (manual)
Denmark	0.0115[*]	
Estonia	0.0310 (RVM)	0.0105 (manual)
Finland	0.03 (RVM)	0.027 (manual)
Lithuania	0.028[*]	
Sweden	0.045(RVM)	0.023 (manual)

[*] There is no separate data for RVM and manual collection.

For the manual collection, the average reimbursement price for Europe is:

RHFmanual = (0.01 + 0.0115 + 0.0105 + 0.027 + 0.028 + 0.023) / 6 = 0.019 euro per PET package

As far as the automatic collection is employed, the average price is:

RHFRVM= (0.02 + 0.0115 + 0.0310 + 0.03 + 0.028 + 0.045) / 6 = 0.028 euro per PET package

For Denmark and Lithuania there is no separate data. For this reason, the common reimbursement price is used for the calculation of the average price in both RVM and manual collection. In order to calculate the annual total compensation capital that DSMO has to pay to retailers, the return rate and the rate of automation are required. For return rate 85 % and 2 billion of PET discarded per year (see Section 3.1), the number of packages to be collected through the Greek DRS is 1.7 billion. With an expected rate of automation 90 % approximately, 1.53 billion PET packages will be collected though RVM and 0.17 billion manually. As a consequence, the annual compensation for automatic collection is:

1.53 billion packages · RHFRVM = 1.53 · 109 · 0.028 = 43 million euros

And for the manual collection:

170 million packages · RHFmanual = 3.2 million euros

As expected, the annual reimbursement for manual collection is quite lower than that of the automatic one. The main reason for this significant difference is the number of RVMs. So, the total annual Retail Handling Fee (RHF) for the deposit system in Greece is 46.2 million euros. To calculate the total annual operating cost, the current analysis should approach the outgoings that are related to other processes, such as transportation cost, operating cost for the nonprofit DSMO and, finally, the outgoings for cutting and compressing the PET packages at sorting facilities/collecting centers. The operating cost for the other processes is calculated to 32 million euros (Table 3), while the total to 78.2 million euros or 0.04 euro per PET package; consequently, the average operating cost amounts to 0.04 euros per PET package.

3.3. Calculation of producer fee

Table 4 presents the main financial data used to calculate the producer fee.

The producers and importers will contribute both for the financial deficit and investment cost. The investment cost is an immediate demand for the operation of the DRS. DSMO in collaboration with producers should decide how the required capital will be collected. In the current analysis, it is considered that the producers, through DSMO, will get a loan to be redeemed during the first 10 years of system operation.

Table 3
Annual operating cost for the Deposit Refund System (DRS) in Greece

Retail Handling Fee per package for manual collection	0.019 euro
Retail Handling Fee per package for automatic collection	0.028 euro
Annual Compensation for manual collection	3.2 million euros
Annual Compensation for automatic collection	43 million euros
Annual Retail handling fee	46.2 million euros
Operating costs for DSMO + treatment of material (PET)	9 million euros
Annual transportation cost	23 million euros
Total annual operating cost of DRS	78.2 million euros

Table 4
The main financial data of the Deposit Refund System in Greece

Investment cost	155 million euros
Operating cost	78.2 million euros
Revenues	58 million euros
Deficit	– 20.2 million euros

Consequently, the producer fee should cover both the financial deficit of 20.2 million euros and the payoff of the loan, amounted to 35.7 million euros in total. This denotes that the producer fee is:

35.7 million euros / 50,000 tons = 714 euro per ton of PET or

35.7 million euros / 2 billion packages = 0.01785 euro per PET package

All the data that describe the operation of the DRS in Greece are summarized and presented in Table 5.

3.4. Statistical data and mathematical model for the DRS in Greece

Based on Table 5, statistical data derive in respect the share of producers' fee, selling material and unclaimed deposits in the revenues of the DRS in Greece (Figure 5). Similarly, data may be used to estimate the share of various components in the operating cost (Figure 6). Correspondingly, Figure 7 shows the effect of automation rate on investment cost.

Figure 5 indicates that the greatest share of the income for the DRS derives from the unclaimed deposits, especially when compared to the revenues from selling materials, which are quite lower. Regarding to the operating cost, the annual transportation cost remains at low level, contrary to the annual retail handling fee that is the most important factor.

Table 5
Features of the DRS in Greece

Total PET packages	2 billion packages, 50,000 tons
Return rate	85 %
Deposit	0.15 euro
Rate of Automation	90 %
Summer monthly working capital	39 million euros
Winter monthly working capital	15 million euros
Annual working capital	300 million euros
Total number of RVMs.	6,000
Annual earnings from unclaimed deposits	45 million euros
Annual earnings from selling bailed PET bottles	13 million euros
Producer Fee	714 euro/ton of PET or 0.01785 euro/package
Annual total revenues	93.7 million euros
Retail Handling Fee for manual collection	0.019 euro/package
Retail Handling Fee for automatic collection	0.028 euro/package
Operating cost	78.2 million euros
Investment cost	155 million euros

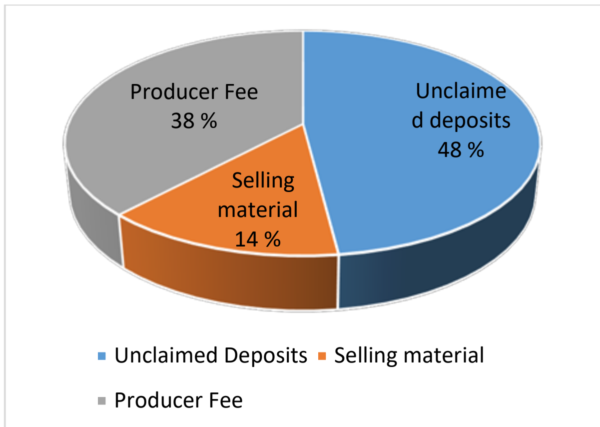

Figure 5. Revenues of the DRS in Greece

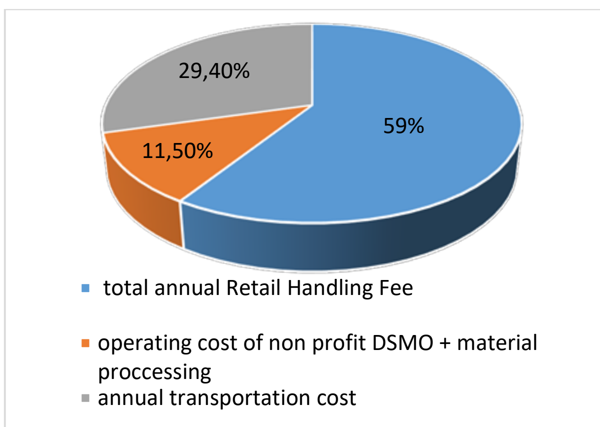

Figure 6. Allocation of the operating cost components of the DRS in Greece

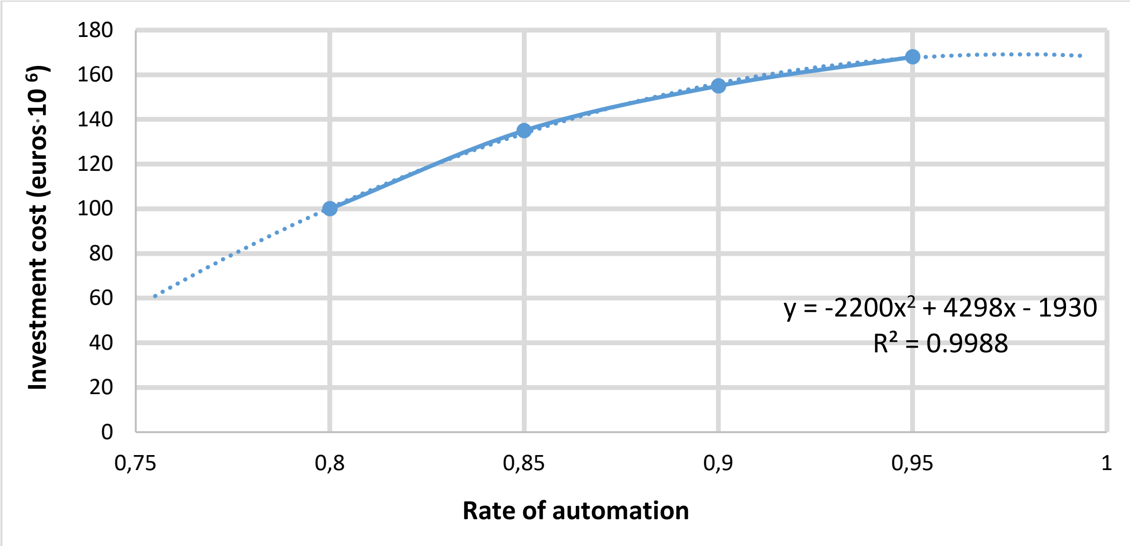

Figure 7. Investment cost as a function of the automation rate for the DRS in Greece

From Figure 7, it is obvious that higher rate of automation implies higher investment cost. However, a DRS operating at extremely high rate is not always efficient. An extremely high rate of automation, for example higher than 95 %, means that even the small retail shops will collect the bailed PET packages automatically. In most cases, the number of packages that are collected in small retailers is not enough to justify a RVM. In this case, the investment cost rises up and the efficiency of the system drops. In contrast, a low rate of automation, 80 % or lower, might affect the return rate negatively, which is the main target of the whole system; in addition, it will surely increase the cost of material processing, because the bailed bottles will not be shredded and compressed for transportation. In conclusion, the rate of automation, combined with other significant factors, such as deposit and return rate, greatly affect the operation of a DRS. Figures 8 and 9 show the correlation between the cost of manual and automatic collection, correspondingly, with automation rate, based on the data for the DRS in Greece.

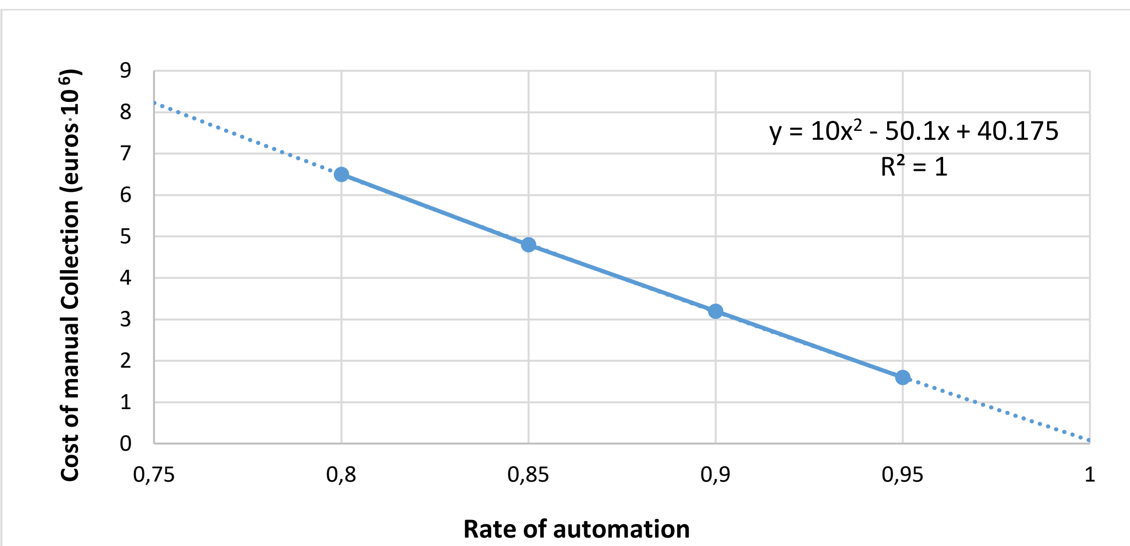

Figure 8. The cost of manual collection as a function of automation rate

The initial choice of automation rate for a new DRS is experiential. However, in the following years, DSMO is responsible to collect all the required data in order to calculate the real rate, under which the system operates, and, by extension, to change it if required.

The following functions can be used to review and modulate the operation of the Greek DRS:

Investment cost:

$$(x) = -2200 \cdot x^2 + 4298 \cdot x - 1930 \qquad R^2 = 0.998 \qquad (1)$$

Manual collection cost:
$(x) = 10 \cdot x^2 - 50.1 \cdot x + 40.175 \qquad R^2 = 1 \qquad (2)$

Automatic collection cost:
$(x) = -28.571 \cdot x^2 + 98.229 \cdot x - 22.16 \qquad R^2 = 0.997 \qquad (3)$

The symbol R^2 is the coefficient of determination; its high values do not necessary divulge the appropriateness of the fitted statistical models. The operation of DRS is complicated; as a result the presented statistical model is being described by many factors compared to the amount of information of the existed literature.

The domain X of each function is the rate of automation. Theoretically, the values, which are assigned to the domain, are defined between [0, 1]. The value "0" represents the case that the DRS operates through manual collection of all packages; as a result, there is no investment cost. Similarly, the value "1" is assigned to the domain X when all packages are collected through RVMs. It is obvious that there is a theoretical explanation for both values, but, in reality, they represent extreme values of no practical usage.

Based on the previous analysis regarding the efficient values of automation rate, in the current case the domain X has been defined in the space [0.75, 1). As a result, the functions can be used for automation rate values from 75 % up to approaching 100 %.

The values of investment cost, manual and automatic collection cost can be easily either calculated from Equations 1-3 or determined from Figures 7-9. From these Figures, it can be concluded that:

- For the function of investment cost, the domain of values is [56, 168). The investment cost will get the value of 56 million euros when the rate of automation is 75 %. Similarly, the maximum investment cost is 168 million euros, when the rate of automation approaches 100 %.
- For the function of manual collection cost, the domain of values is [8.3, 0). The manual collection cost rises up to 8.3 million euros and tends to become zero as the rate of automation approaches 100 %.
- As for the function of automatic collection cost, the domain of values is [35, 48). The automatic collection cost starts with 35 million euros, when the rate of automation is 75 %, and rises up to 48 million euros when automation rate approaches 100 %.

Summing up the aforementioned costs, regarding automatic, manual collection and investment cost, a new function derives:

Cost (x) = Investment cost (x) + manual collection cost (x) + automatic collection cost (x)

Cost (x) = -2218.571 x2 + 4346.129 x -1911.985

The domain X of the function is the rate of automation with values from 0.75 to 1 or 75 % to 100 %, as it has already been pointed out.

With the aid of Geogebra, an interactive statistics application, it is feasible to present the graph of the Cost function (x).

The domain of the function is restricted in order to present the graph for the rate of automation from 75 % to 100 %. As shown in Figure 10, as the rate of automation rises, the cost also increases. This increase is expected and can be mathematically explained by comparing the monotonicity of the functions that were inserted into Equation (4). To conclude, the increase of automation rate of an operating DRS results into severely higher cost.

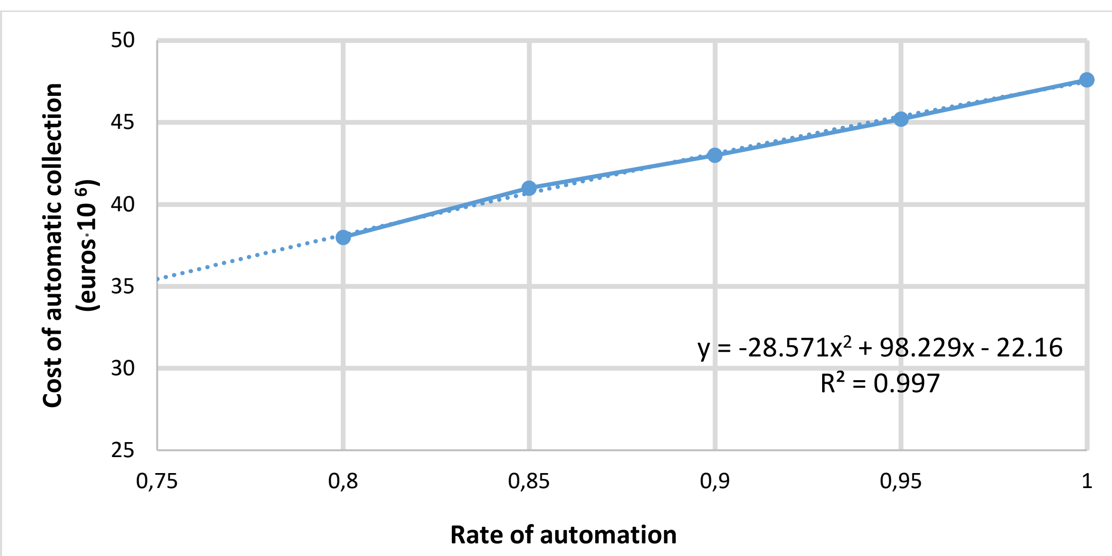

Figure 9. The cost of automatic collection as function of automation rate

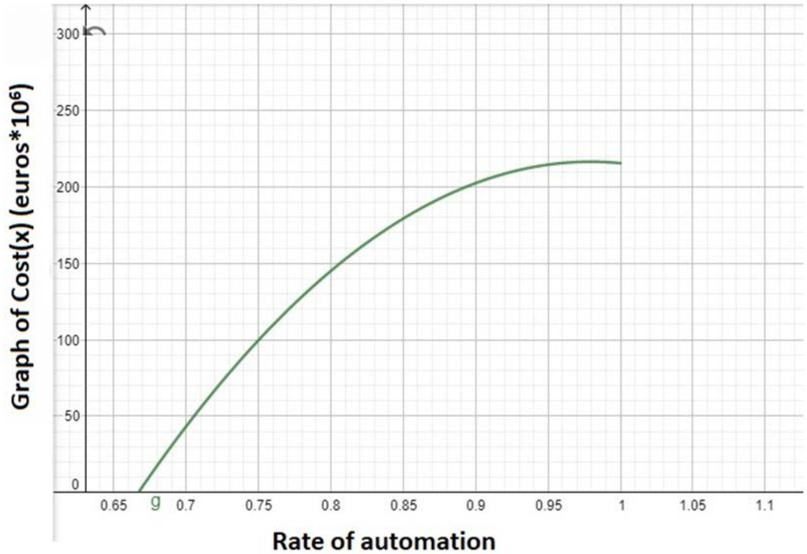

Figure 10. Graph of cost vs. automation rate restricted approximately in the range [0.75, 1)

However, it is already mentioned that a rate of automation lower than 75-80 % negatively affects the environmental goal. As a result, the increase of the automation rate in order to improve the existing return rate of an operating DRS should be the least preferable action considered by DSMO. In case of missing the target, the first action to be taken by DSMO is to re-examine the positions of RVMs in order to make sure that they are distributed properly.

In conclusion, the rate of automation is a key factor for the operation of the Deposit Refund System (DRS). One more vital component is the return rate. The importance of the return rate can be seen in Figure 11, which presents 5 scenarios for the Greek DRS with different return rates while all the other factors remain constant.

Figure 11 shows that for return rate 85 % there is annual financial deficit of 20.2 million euros, which will be covered by producer fee. On the other hand, return rate of 75 % implies financial surplus of 16.95 million euros annually. Although operating costs would be decreased because of the less retrieved packages, this surplus corresponds to the case of almost unclaimed deposits, which the DSMO get as revenues due to lower return rate. At higher return rates, the financial deficit increases, as expected, and finally reaches to 53.6 million euros for return rate of 95 %. From Figure 11, it is obvious that the DRS requires extremely big financial support to achieve high return rates; in contrast, DSMO would have enough profit to repay the loan at low return rates scenarios. The relation between the financial balance of DSMO and the return rates is clearly seen in Figure 12.

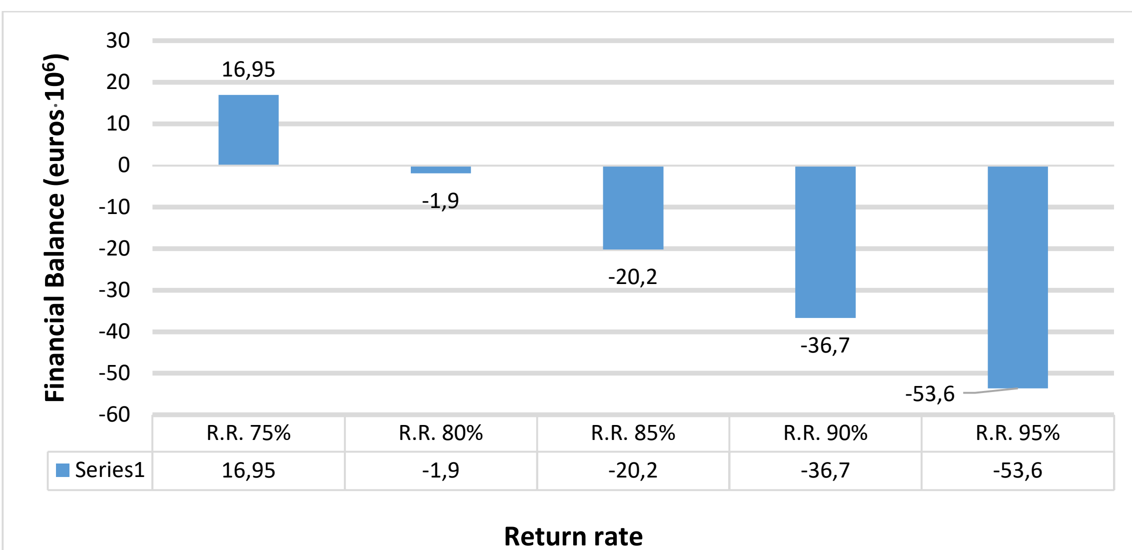

Figure 11. The financial balance of the Greek DRS for various return rates

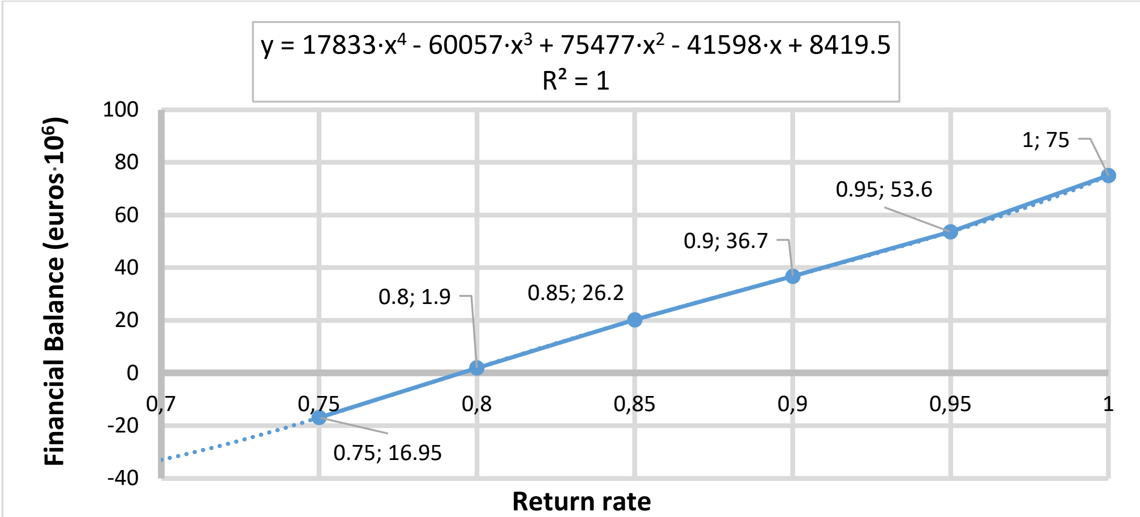

Figure 12. The financial balance of the Greek DSMO as function of the return rate

In Figure 12, the negative values of vertical axis represent a financial surplus for DSMO, while the positive ones depict a financial deficit.

The function that describes the relation between the financial balance (F.B.) and the return rate (x) is:

F.B.(x) = $17833 \cdot x^4 - 60057 \cdot x^3 + 75477 \cdot x^2 - 41598 \cdot x + 8419.5 \quad R^2 = 1$ (4)

The F.B. function such as (1), (2), (3) is derived from the model-based approach of the present paper. The approach started with two major estimations based on the data of existing European deposit systems:

1. A deposit of 15 cents will entrain roughly a return rate of 85% (section 2.2 “Setting the merit of a deposit”).
2. The Greek DRS requires approximately 6,000 RVMs in order to operate at 90 % rate of automation. The high return rate utterly configures the investment cost and portion of the operating cost, such as transportation cost (section 3.2 “Investment and operating cost”).

Entrenched on these two estimations, the paper sets scenarios where the Greek DRS operates on different return rates and rates of automation. However, in these scenarios, a major assumption is made. While rate of automation changes (see Figures 7, 8, 9), all the other factors (for instance return rate and transportation cost) remain constant. The same observation is in force in Figures 11 and 12, where the independent variable is the return rate. Under real conditions, an increase of the rate of automation could lead to raise of return rate. The domain X of the function is the return rate and, as previously mentioned, it can get values in the space [0.7, 1), namely from 70 % up to the theoretical value of 100 %.

The domain of the function F.B.(x) can get values from -33.21 million euros, which corresponds to profit for the DSMO, up to 75 million euros as deficit, that is to say [-34, 75). The equation F.B.(x) = 0 is realized for the value of the domain x=0.7957, which means return rate 79.57 %. Practically, the DSMO demands no financial support from the producers at the point (0.7957, 0) of the Cartesian coordinate system. As a result, the revenues of the system would be able to cover the operating costs with no need of producer fee.

The relation between the producer fee and the return rate can be seen in Figures 13 and 14. The difference between the Figures 13 and 14 is the process of calculating the Producer Fee. Regarding Figure 13, producer fee is calculated to cover the financial deficit for different return rates, while as for Figure 14 the producer fee is calculated to repay both financial deficit and annual capital required to pay off a 10-year loan for the investment cost.

3.4. Effects and impacts

The biggest advantage of the DRS establishment in Greece is the return rate, which is expected to be very high. Practically, it is expected to collect approximately 42,000 tons of PET per year; in turn, this means that 25,000 tons of PET will be added up to the recycling system, which otherwise would end up in the sea or in landfills. The production of one PET bottle generates approximately 82.8 grams of CO_2 emissions (Razis and Christopoulos, 2021). Taking into account that the ratio of packages 0.5 liter to1.5 liter is 1:1 and the corresponding weight of each package (also see Section 3.1), it can be concluded that the 25,000 tons of PET correspond to 1 million PET packages. Consequently, if not recycled, approx. 82,800 tons of CO_2 emissions should had been released to replace the lost PET packages and cover the consumption needs.

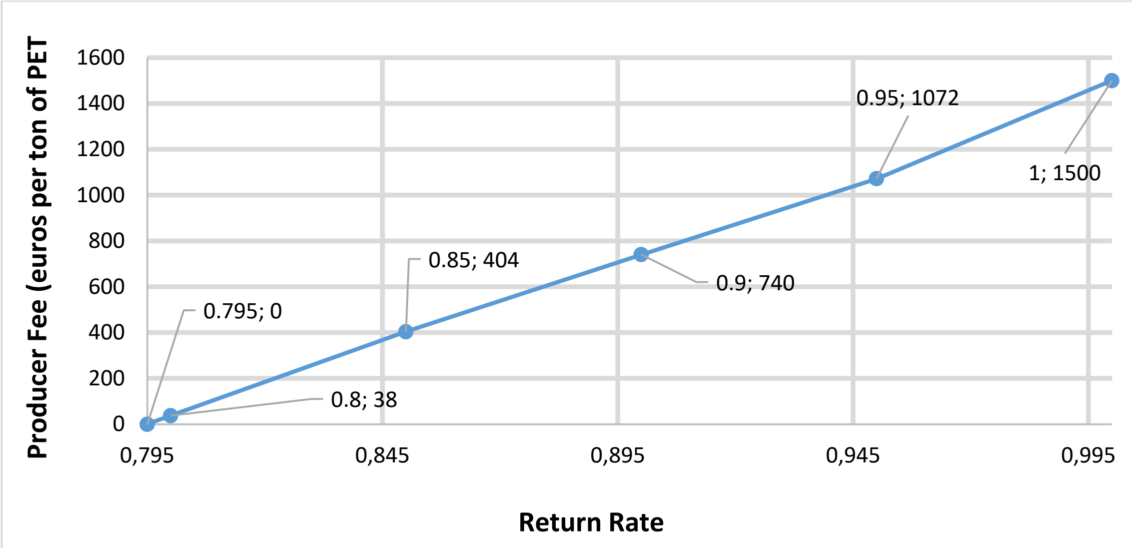

Figure 13. Producer Fee as function of Return Rate

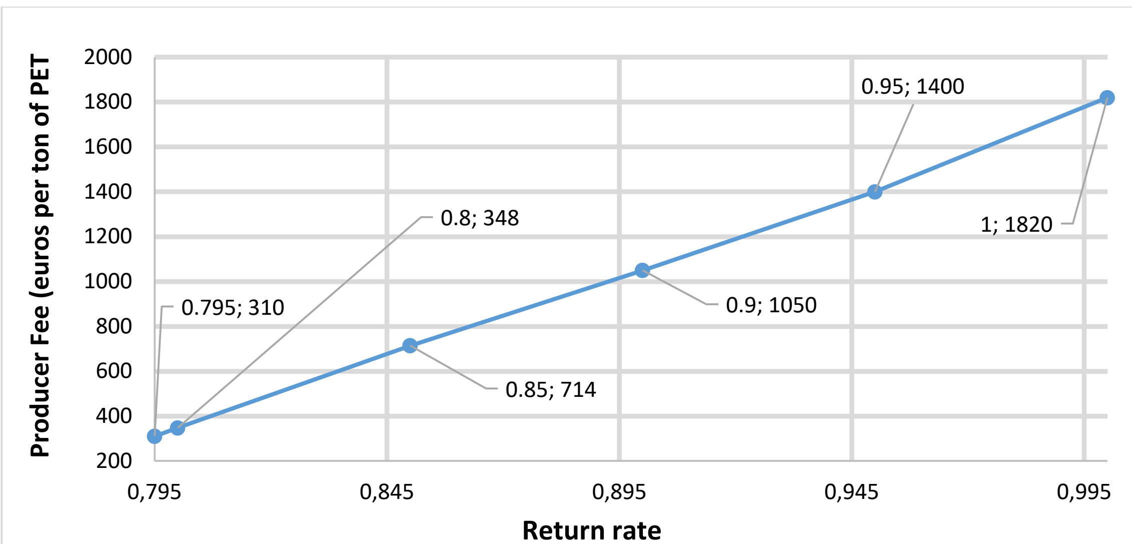

Figure 14. Producer Fee, calculated to cover both the financial deficit and the investment cost, as function of return rate

The recycling of packages can reduce the CO_2 emissions by 30-70 %, with the exact rate depending on many factors, such as the selected recycling system and the adaptation of the system to the needs of the country. Therefore, the DRS in Greece could annually reduce the CO_2 emissions by 24,000 - 58,000 tons.

Furthermore, the establishment of the DRS in Greece will provide a better control of the material and, by extension, of the whole system, in comparison with the existing EPR model, whose most data are based on estimations. Finally, it will result in the reduction of cleaning costs for the local authorities.

On the other hand, the main drawback is the financial burden of the DRS. Both investment cost and operating cost of the system are quite high, especially in comparison with the existing EPR model. The investment cost is estimated from 90 to 155 million euros (Razis and Christopoulos, 2021), depending on the strategic decisions that DSMO has to make. This cost will lead to a financial transaction between Greek State and a foreign company, since there is no Greek manufacturer to provide the RVMs. As a result, there will be no other sector of the Greek economy to be involved and take benefit of this capital.

The establishment of the DRS in Greece will negatively affect the operation of the existing recycling model EPR. For the EPR model, PET is a material with financial surplus; basically, the PET packages support the collection of the other materials such as glass and paper. As a result, the operation of the DRS in Greece will decrease the revenues of the existing model. In case of including aluminum packages to DRS, the EPR revenues will be reduced drastically.

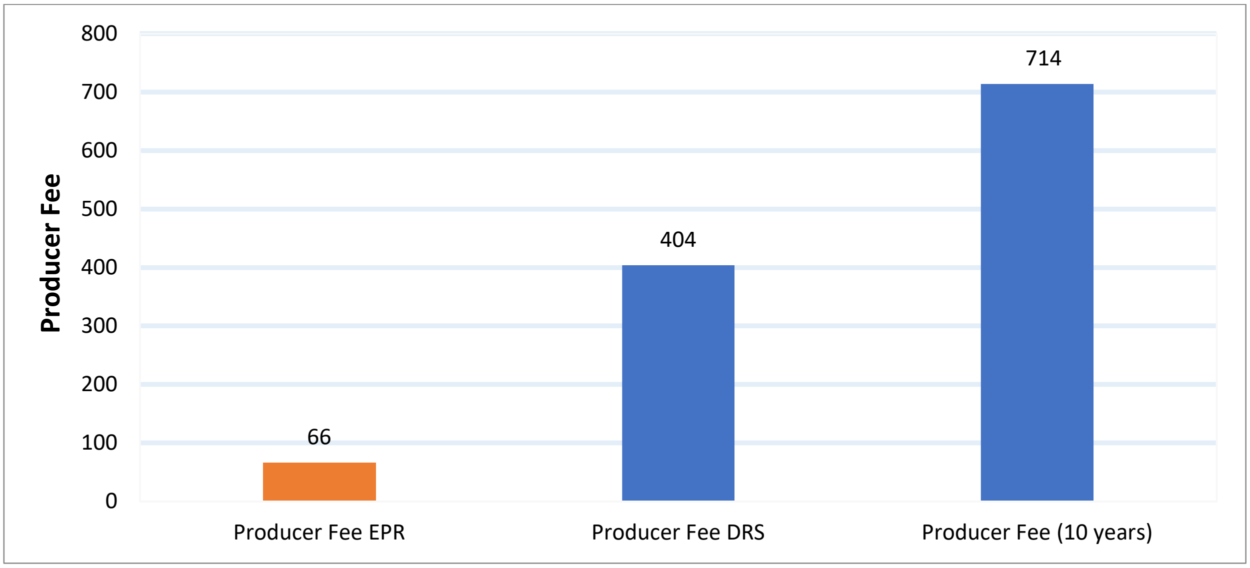

Figure 15. The producer Fee for the Greek DRS and the existing EPR model

The Producer Fee of PET material for the EPR model is 66 euro per ton of material (Razis and Christopoulos, 2021), contrary to DRS model where the Producer Fee is 404 and 714 euro per ton of PET (also see Section 3.3), including investment cost. In conclusion, the financial support necessary for the operation of the Greek DRS is 6 to 10 times higher than that of the EPR (Figure 15).

As Figure 16 indicates, PET is a profitable material under the current EPR system while the outcome under DRS is financial deficit for high return rates.

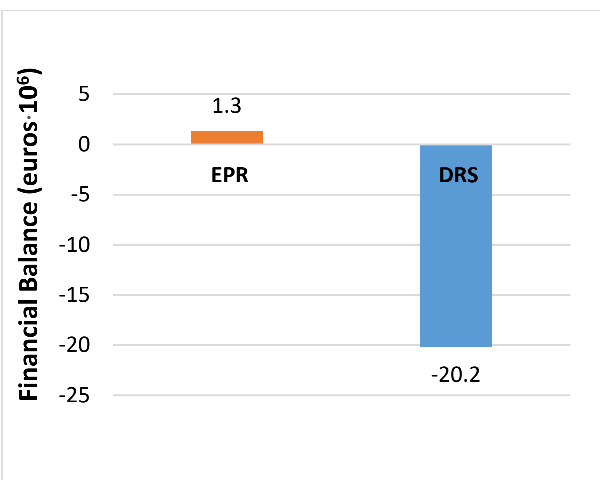

Figure 16. The annual financial balance of PET material for EPR and DRS

EPR model is estimated to collect annually 17,000 tons of PET approximately. As a result, the total amount of capital required to support the collection of the material is:

17,000 tons · 66 euro per ton of PET = 1.12 million euros

Taking into account that the population of Greece is 10 million, the financial burden per capita for the EPR model, regarding PET material, is 0.112 euro per capita.

As for the DRS, with expected return rate 85 % there is a financial deficit of 20.2 million euros or 36.7 million in case of including the investment cost (also see Section 3.4), which denote a financial burden 2.02 or 3.67 euros per capita correspondingly; the producer fee is estimated to be 404 or 714 euros per ton of material (also see Section 3.3).

To compare, the financial burden per capita for the DRS in Greece is 20 to 32 times higher than the corresponding of the EPR system that is currently applied (Figure 17).

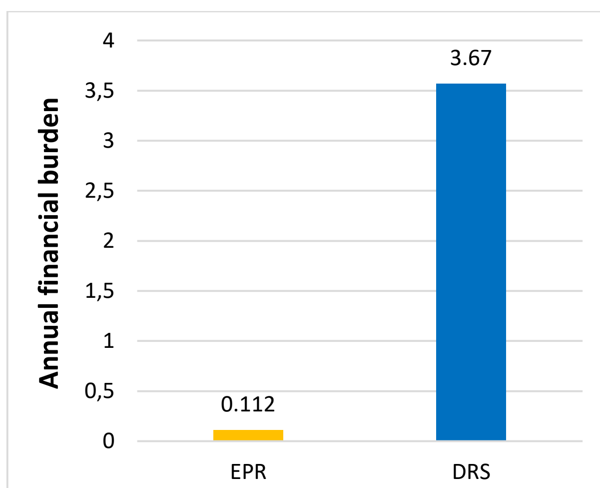

Figure 17. The annual financial burden per capita for DRS and EPR system in Greece

In Table 6 the advantages and the drawbacks of the establishment of the Greek DRS are briefly presented.

Table 6
Benefits and disadvantages of the establishment of DRS in Greece

Benefits	Disadvantages
High return rate	High investment and operating cost
Annual reduction of CO_2 emissions	Unfavorable ratio of cost and environmental outcome
Endorsement of circular economy	Binding decision for the future of national recycling system
Better control of the material and, generally, of the whole collection system	Indirect financial burden of EPR system
Discharge of the local governments from collecting PET material	High financial burden for the Greek society in comparison with the existing system
	Interaction of DRS with a great number of retailers
	Disputable environmental outcome

4. Conclusions

This study clearly shows that the establishment of a DRS (Deposit Refund System) in Greece will increase the return rates for plastic containers which is quite important for Greece, considering the great pollution of Mediterranean Sea from plastic leakage. Furthermore, DRS will especially benefit the Greek islands, which attract thousands of tourists every year. However, the operation of the system will burden the Greek citizens. The investment cost of DRS is quite high compared to the annual funding of other important sectors such as public health-care system, public education, or the existing funding of recycling. The Greek State, society and science community should examine in length the application of this system. Finally, it has to be noted that aluminum packages should be incorporated into the DRS, in order to take maximum advantage of the high investment cost. In case of adding more materials to the DRS, there should be financial support for the existing EPR model, so there will not be any undesired results on the environmental targets of the other materials.

To globally approach an ideal circular economy, there must be a combined effort towards three main directions (Figure 18):

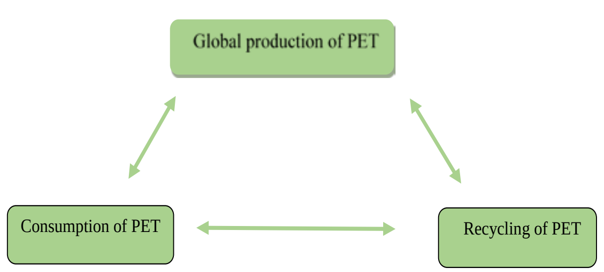

Figure 18. The three main factors for approaching Circular Economy (Mavropoulos and Nilsen, 2020)

- Promoting the recycling of materials though collecting the bailed packages and processing them to re-enter the production.
- Changing the global production of all goods such as energy and products by designing new products with bigger life cycle based on recycled raw materials.
- Reducing the consumption of products in general.

These three factors are important and should be equally promoted in order to entirely achieve the environmental goals. Advancing the recycling without reducing the global consumption of all goods will turn the recycling into a reason for even more consumption, which means even more pollution of the planet regardless of the effectiveness of the established recycling systems. Similarly, promoting the recycling without changing the global production of goods will lead to partial limitation of the waste without providing the environmental issues with actual solutions. Establishing new systems for plastic recycling or designing new alternative products for single-use plastic products, such as plastic straws, is not sufficient means to cope with the growing plastic production in the following years.

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Uspostavljanje sistema povraćaja depozita za PET ambalažu u Grčkoj: ekonomska analiza, prednosti i posledice

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Sistem povraćaja depozita za PET amabalažu
Evaluacija Sistema povraćaja depozita u Grčkoj
Reciklaža PET amabalaže

I Z V O D

Ovaj rad se bavi uvođenjem Sistema povraćaja depozita kao novog sistema reciklaže u Grčkoj za PET ambalažu, a u skladu sa Evropskom direktivom 2019/904. Osnovna svrha ovog rada je predstavljanje analize troškova i prednosti, koja se bavila procenjivanjem sugestija i uticaja koje bi pomenuta direktiva imala u Grčkoj. Pored analize troškova i prednosti koje bi sistem imao, izvršeno je i poređenje između ovog modela i postojećeg modela reciklaže za PET ambalažu kako bi se otkrio njihov uticaj u Grčkoj. Pored toga, uspostavljen je i matematički model zasnovan na podacima o reciklaži PET ambalaže u Grčkoj. Ovaj model opisuje rad odgovarajućeg Sistema povraćaja depozita u Grčkoj, a mogao bi biti koristan za razumevanje, uspostavljanje i poboljšanje ovakvog sistema za druge otpadne proizvode.

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Design Steps and Performance of Aerated Lagoon, Oxidation Ditch and Wetland Methods for Erbil Municipal Wastewater Treatment and Reusing

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A B S T R A C T

The objectives of the current study were to investigate the characterization, treatment techniques and reuse of fresh municipal wastewater (MWW) from the east-south area of Erbil city, Kurdistan Region, Iraq. The collected wastewater samples were analyzed for 21 quality parameters. Some of the quality parameters such as color (146 Pt. Co and 337 Pt. Co), total solids (800 mg/L), suspended solids (400 mg/L and 1100 mg/L), nitrate (17.7 mg/L), nitrite (11 mg/L and 29 mg/L), and ammonia (2.09 mg/L and 2.64 mg/L) exceeded the standards for wastewater disposal. Accordingly, treatment was required before the wastewater could be discharged to the natural environment. Treatment techniques such as aerated lagoons, oxidation ditches, and wetlands were designed and investigated. Design procedures, calculations, and performance for each treatment method were explained. The total area designed for aerated lagoons, oxidation ditches, and wetlands was 72000 m^2, 17180 m^2, and 25200 m^2, respectively. In general, the wetland method was the most effective method with efficiencies of 91.6 % for biochemical oxygen demand, 90.4 % for chemical oxygen demand, 85.7 % for ammonia, and 91.8 % for suspended solids. Treated wastewater can be reused for irrigation purposes and is completely safe for irrigation. The use of treated wastewater from the east-south part of the city of Erbil for irrigation instead of drinking water is economical and leads to the conservation of drinking water sources.

1. Introduction

The expansion of urban populations and increasing attention to domestic water supply and sanitation are resulting in greater volumes of municipal wastewater (MWW). Given the importance placed on environmental health and water pollution, there is a growing awareness of the need to dispose of this wastewater in a safe and

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beneficial manner. The use of wastewater in agriculture could be an important issue when planning disposal in arid and semi-arid areas. However, it should be realized that the amount of wastewater available in most countries will be a small fraction of the total water demand for irrigation. However, the use of WW will lead to the protection of higher quality water and its use for purposes other than irrigation. Since the negligible cost of an alternative supply of good quality water is generally higher in areas of water scarcity, it makes sense to integrate agricultural reuse into water resource and land use planning (Pescod, 2013). Water reuse is a fundamental component of water demand management that promotes the protection of high-quality freshwater and reduces both pollution and overall supply costs (Shakir et al., 2017).

Increasing efficiency in crop management and continuous increase in crop yields have increased the demand for water resources for irrigation purposes. In many countries around the world, WW is reused for irrigation purposes (Toze, 2006; Al-Murshady et al., 2021; Kesari et al., 2021; Ramirez et al., 2021; Ortega-Pozo et al., 2022). In many countries, water is becoming an increasingly scarce resource and planners are forced to consider all sources of water that can be used economically and efficiently to support further development. At the same time, as the population is growing at a high rate, increasing food production appears to be critical. One of the first reasons for this problem is that the proportion of water available for human consumption in rivers and streams, lakes, reservoirs, and aquifers is not evenly distributed throughout the world (Sophocleous, 2004). The authors noted that agriculture has increased in recent decades, which has increased pressure on groundwater resources and the need for pumping energy, and has affected the North Western Sahara Aquifer System (NWSAS). The NWSAS is located in North Africa and covers large areas in Tunisia, Algeria, and Libya. It holds invaluable groundwater resources that are necessary for sustaining livelihoods in the area. Therefore, researchers have planned another source for irrigation instead of groundwater, through the treatment of wastewater and reuse for agriculture (Ramirez et al., 2021). Due to drought years and impact on water resources and direct use of raw wastewater for irrigation in Erbil, Babylon, Karbala, Diwaniya, and Najaf provinces in Iraq, wastewater has been treated to replace water sources and ensure acceptable water quality for irrigation (Aziz et al., 2019; Al-Murshady et al., 2021). Because there is not enough irrigation water available, many low-income countries in Asia. Africa, and Latin America use untreated WW as a source for irrigation. In contrast, middle-income countries, such as Jordan, Tunisia, and Saudi Arabia, use treated wastewater for irrigation (Kesari et al., 2021). In addition, China tops the list of Asian countries for wastewater reuse with an estimated $1.3 \cdot 10^6$ hectares, including India, Vietnam, and Pakistan (Kesari et al., 2021).

Consequently, 40 % of the total land area is arid and includes climatic zones classified as arid, semi-arid, and dry sub-humid (Koohafkan and Stewart, 2008). At the same time, the increasing demand for water resources is a result of population growth, economic development and raising the standard of living, climate change, and pollution (Mujumdar, 2013).

It is estimated that more than 40 % of the world's population will face water stress or scarcity in the next 50 years, providing a serious incentive to find sustainable management options for water resources (WHO, 2006). Reuse of treated wastewater (TWW) is a viable option that is being forced in some cases by the lack of viable alternatives. In addition to reducing the use and withdrawal of freshwater, wastewater reuse also helps reduce the discharge of wastewater into freshwater ecosystems. In this scenario, WW increasingly becomes a valuable resource rather than a waste product. Certainly, irrigation with treated wastewater is already practiced, mainly in agriculture and landscaping (Bixio et al., 2006; Aziz et al., 2019; Aziz, 2020; Al-Murshady et al., 2021; Ramirez et al., 2021; Ortega-Pozo et al., 2022).

Wastewater in Erbil city is composed of domestic, commercial, washing and industrial sources. On the other hand, irrigation with wastewater raises health problems (risks of viral and bacterial infections for both the farmer and the plants) and agronomic problems due to the presence of toxic substances. To avoid health risks and damage to the natural environment, wastewater must be treated before being used for agricultural and landscape irrigation.

Nowadays, as climate change is affecting water resources and droughts are becoming more frequent, measures to adapt to the effects of climate change are urgently needed. To solve this problem, water can be used for irrigation in agriculture.

The main goal behind reusing wastewater is to close the water cycle on a much smaller, local scale. In this way, once properly treated, wastewater becomes a valuable water resource rather than a waste to be disposed of. Water reuse is the most difficult decision to make because these water sources are the lowest quality and therefore require advanced treatment.

Rapid climate change can lead to long periods of drought that directly affect the availability and dependence on groundwater for irrigation. During long periods of drought, there is a greater risk that aquifers will dry up, especially if they are small and shallow. In this case, irrigation cannot depend on groundwater for this reason. Irrigation from groundwater should be reduced and more groundwater should be recharged by treated water. This can be done by two methods (1) surface application or infiltration and (2) direct injection into the aquifer (Asano, 2006).

The disposal of wastewater from the east-south part of

Erbil city causes problems for the natural environment. Therefore, the wastewater generated must be treated before it is discharged into the environment or used for irrigation. In addition, depletion of groundwater table and use of potable water for irrigation are other shortcomings in the water sector of Erbil city. The objectives of the present work were to 1) study the characteristics of raw wastewater from the east-south part of Erbil city, 2) present suitable treatment methods such as aerated lagoons, oxidation ditches, and wetlands, and 3) reuse the wastewater for irrigation purposes in Erbil city. In the literature, aerated lagoons, oxidation ditches and wetlands have been used to treat urban wastewater (USEPA, 2000; Gikas and Tsihrintzis, 2014; Hadisoebroto et al., 2014; INDITEX, 2015). To date, this type of study has not been conducted in Erbil City.

2. Material and Methods

2.1. Site description

Erbil is the capital of the Kurdistan Region of Iraq. It is located about 350 km north of the city of Baghdad. The population of Erbil City is about one million people. Its boundaries extend from longitude 43° 15' E to 45° 14' E and latitude 35° 27' N to 37° 24' N. The canal that carries sewage is located at 36° 08.780' N and 044° 04.203' E. Sewage from Zeelan City, Hawkary Q., part of Hasarok 5 Q., Alton City, Zagros Q., Zaiton City, Ala City and Awenae Shar City flows into the said canal. In addition, the discharge (Q) was measured at the site and was 0.5 m^3/sec.

2.2. Sample collection

Samples were collected in clean containers in the east-south area of Erbil city. Fresh wastewater samples were collected in commercial 1.5-L plastic containers. During this investigation, two water samples were collected on February 25, 2018 and March 27, 2018. In accordance with the Standard Method for Water and Wastewater Testing, American Public Health Association (APHA) (2005). Samples were immediately transported to the Sanitary and Environmental Engineering Laboratory and stored in a dark, cold room at 4 °C prior to experimental use to avoid biological activity and changes in the samples. Samples were collected from the surface at a depth of approximately 30 cm.

WW samples were analyzed for their chemical and physical properties. The experiments were performed according to (APHA, 2005). The following parameters were tested: pH, oxidation-reduction potential (ORP) (mv), total dissolved salts (TD salts) (mg/L), temperature (^{o} C), total solids (TS) (mg/L), total suspended solids (TSS) (mg/L), total dissolved solids (TDS) (mg/L), total volatile solids (TVS) (mg/L), total nonvolatile solids (TnVS) (mg/L), total acidity (mg/L), total alkalinity (mg/L), total hardness (mg/L), biochemical oxygen demand (BOD5) (mg/L), turbidity (FTU), chloride (mg/L), chemical oxygen demand (COD) (mg/L), color (Pt.Co.), dissolved oxygen (DO) (mg/L), electrical conductivity (EC) (µs/cm), ammonia (mg/L), nitrite (mg/L), and nitrate (mg/L). The experiments were conducted at the Sanitation and Environment Laboratory, Department of Civil Engineering, College of Engineering, Salahaddin College of Erbil, Erbil, Kurdistan Region, Iraq. The following equipment and procedures were used to measure WW properties. The water temperature of the samples was measured in the field using a clean mercury thermometer with an accuracy of 0.1 °C. Turbidity was measured in the laboratory using the Model WTW 550 Germany turbid meter. EC and pH were measured using the Combined CCMD 625. The total salt was determined mathematically from the EC values. Total acidity, total alkalinity, total hardness, and chloride were determined using titration methods in accordance with APHA Standard (2005). BOD5 values were determined based on values from DO at initial collection and after five days. TS TSS and TDS were determined using an oven, filter paper, evaporating dish, flask, and sensitive electric balance. Color, COD, ammonia, nitrite and nitrate were measured using spectrophotometer DR 3900. A multi-parameter instrument was used to measure the redox potential.

2.3. Treatment approaches

Aerated lagoons, oxidation ditches, and wetlands were proposed for treating Erbil's wastewater. Each method was designed based on the collected data or available data and equations in the references. Design procedures, calculations, details and drawings, separation efficiency, advantages and disadvantages were explained for each treatment technique.

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3. Results and Discussions

3.1. WW characteristics

Raw sewage from the east-south area of Erbil city is generally composed of: 1) domestic wastewater from households generated by dishwashers, washing machines, bathtubs and toilets, which may contain organic and inorganic substances in suspended, colloidal and dissolved forms, 2) commercial and institutional areas, and 3) rainwater that enters the sewer system during the rainy season and washing.

The experiments conducted are listed in Table 1. The parameters such as temperature, pH, BOD5, COD and chloride were within the permissible limits specified in the standards. However, the limits were exceeded for other parameters such as color, TS, TSS, nitrate, nitrate and ammonia. Consequently, the treatment of wastewater in the east-south part of Erbil city is necessary. The low BOD5 and COD values are due to the dilution of wastewater by other types of wastewater with low BOD values entering the sewer. Higher values of BOD5 and COD were reported in the literature for Erbil wastewater (Mustafa and Sabir, 2001; Aziz, 2004, Aziz and Ali, 2017; Aziz, 2020). Erbil MWW can be considered as weak WW (Metcalf and Eddy, 2014). From the documented data, parameters such as pH, temperature, and chloride were in accordance with the standards for wastewater disposal, while TSS and BOD5 exceeded the standards (Mustafa and Sabir 2001; Ali, 2002; Aziz, 2004; Shekha, 2008; 2013; Aziz and Ali, 2017; Aziz, 2020). In the literature, wastewater samples were analyzed at another site in Erbil City and some parameters such as BOD5, COD, ammonia, manganese, phenols, oil and grease, TS, TSS and TDS exceeded the standards for wastewater disposal (Aziz and Ali, 2017; 2018). Therefore, treatment of wastewater in Erbil city was proposed using different methods such as aerated lagoon, oxidation pit and wetland for wastewater reuse.

Table 1
Characteristics of raw Erbil municipal WW

No.	Parameter	Unit	Value Feb. 25th, 2018	Value March 27th, 2018	Standards*
1	Temperature	°C	13.4	23	40
2	pH		7.82	7.7	6.5-9.6
3	EC	µs/cm	580	573.65	-
4	Total Acidity	mg/L	24	40	-
5	Total Hardness	mg/L	160	160	-
6	Total Alkalinity	mg/L	192	252	-
7	Turbidity	FTU	12.7	11.3	-
8	Chloride	mg/L	38	52	750
9	Color	Pt. Co	146	337	Nil**
10	TDS	mg/L	200	400	-
11	TS	mg/L	200	800	500
12	DO	mg/L	7.9	7.2	-
13	BOD_5	mg/L	4.1	5.6	40**
14	COD	mg/L	8	10	100**
15	TSS	mg/L	400	1100	35
16	TVS	mg/L	200	700	-
17	TnVS	mg/L	200	400	-
18	Ammonia	mg/L	2.09	2.64	1
19	ORP	mv	-175	-189.7	-
20	Nitrate (NO_3-N)	mg/L	2.6	17.7	10
21	Nitrite (NO_2-N)	mg/L	11	29	1

* According to environmental protection regulation EPA (2003)
** Iraqi Environmental Standard (2011)

3.2. Treatment methods

3.2.1. Aerated lagoons

The aerated lagoon is one of the most widely used methods of wastewater treatment in the world, and also one of the simplest and least expensive systems. Lagoons are basins designed to receive, store and treat wastewater over a period of time. Lagoons are equipped with mechanical aerators to maintain an aerobic environment and prevent the settling of suspended biomass. Aerated lagoons can be divided into two types: Aerated lagoons with suspended growth (completely mixed lagoons) and facultatively aerated lagoons (partially mixed lagoons). The difference between these two types is the degree of mixing of the lagoon contents. Fully mixed lagoons provide sufficient aeration or mixing to keep solids in suspension, while partially mixed lagoons are designed so that settleable solids accumulate on the lagoon floor where they are anaerobically decomposed. Generally, lagoons are lined with materials such as clay that prevent effluent from leaching into the underlying groundwater. Wastewater in the lagoons undergoes a variety of treatment methods, including physical, biological, and chemical processes. Most of the treatment occurs naturally, but some systems are designed to also use aeration devices that increase oxygen levels in the wastewater (Kamyotra and Bhardwaj, 2011). An aerated lagoon is designed to have flow through it, an influent on one side and an effluent on the other, and to retain the effluent for a period of time. The treatment plant for MWW consists of a fine screen, two or three aerated lagoons in series or parallel, and a treatment lagoon.

i) Design of aerated lagoons

Each lagoon system must be individually designed for its particular location and use. The design of lagoons is based on several factors such as the type and amount of wastewater to be treated and the level of treatment required by law, the type of soil, the climate, the available land area, and the amount of sunlight and wind. After the wastewater leaves the lagoons, it usually must undergo an additional treatment called polishing. This treatment is used to remove pathogenic organisms or nutrients from the wastewater. After this stage, the wastewater is considered treated and can be returned to the environment. The depth of the polishing lagoon should be about 1.20 m (Qasim, 2017). There are two bases on which the design of aerated lagoons is based: volume loading and residence time.

There are different forms of lagoons. The most common shape for treatment plants is the rectangular shape, which allows good circulation and mixing with lower energy requirements. The corners of the lagoon should be curved and the slope should not exceed a 2:1 ratio (width to height).

The water depth is usually set at 2.5 m and the depth of the lagoon should be between 2 and 3 m. The slope angle depends on the type of soil on which the lagoon is built. As a rule, it is 1:1.5 to 1:2. A natural or clay lining should be used. If the soil is highly permeable, a plastic liner can be used to protect the areas and prevent water leakage. Another problem with lagoon design is the damage caused by muskrats and plants. The solution to this problem is to reinforce the embankments at the level of the normal water table.

In the range of 0.44 to 2.2 m^3/sec, four tanks are often provided to allow operational flexibility and ease of maintenance (Metcalf and Eddy, 2014).

Kinetic coefficients of interest in the design of an aerated lagoon:

Design procedure

Measured discharge at the site,

$$Q = 0.5\ m^3/s = 43200\ m^3/d$$

Assumed water depth = 3 m and width of basin = 4.5 m (Metcalf and Eddy 2014). In addition, the suggested depth for an aerated lagoon varies from 3 m to 4.5 m (Hill, 2015). The USEPA (2002) also indicated that the typical depth of an aerated lagoon is 3 m. Determine the area of the lagoon based on the SRT,

SRT=5 d (Metcalf and Eddy, 2014)

In addition, USEPA (2002) stated

$$\text{Volume (V)} = Q \cdot SRT = 43200 \cdot 5 = 216000\ m^3$$

Surface area of the lagoon

Area= Volume / Depth

$$Area = \frac{216000\ m^3}{3} = 72000\ m^2$$

Determination of lagoon temperature according to Eq. (Metcalf and Eddy, 2014)

$$Tw = \frac{AFTa + QTi}{AF + Q} \quad (1)$$

where:

Ti is the temperature of the inflowing wastewater, ˚C
Tw is the temperature of the lagoon water, ˚C
Ta is the air temperature, ˚C
A is the surface area, m^2
Q is WW flow rate, m^3/d

Two samples were collected on 25th February and on 27th March. The average of the two temperatures was taken.

$Ta = 23\ celsius,\ \ Ti = 18.2\ celsius, and\ A = 0.489\ m^2$
$Assume\ Q = 0.3\ m^3/s$
$Q = 25920\ m^3/d, F = \ 0.5\ in\ SI\ system$

$$Tw = \frac{0.489 \cdot 0.5 \cdot 17 + 43200 \cdot 13.4}{0.489 \cdot 0.5 + 43200} = 18.2\ °C$$

Estimation the soluble discharge (Metcalf and Eddy, 2014):

$$S = \frac{k_s \cdot [1 + (k_d)SRT]}{SRT \cdot (Y_k - k_d) - 1} \quad (2)$$

Kinetic coefficients (Metcalf and Eddy, 2014):

$K = 5\ g\ per\ g.d,\ \ Ks = 60\ g\ /m,\ \ \ \ Kd = 0.10\ g\ per\ g.d,$ $Y = 0.6\ g\ per\ g,$ For 20 ˚C

$$S = \frac{60 \cdot [1 + (0.10) \cdot 43200]}{43200 \cdot \left((0.6 \cdot 5) - 0.10\right) - 1} = 2.069\ g/m^3$$

1 - Estimation of the BOD of the waste water

a) Correct the removal rate constant for temperature effects using Eq. 3 (Metcalf and Eddy, 2014):

$$k_T = k_{20}\theta^{(T-20)} \quad (3)$$

where:

k_T is the BOD reaction coefficient at temperature T, 1/d
k_{20} is the BOD degradation rate at 20 ˚C, 1/d
θ is the temperature coefficient 1.06
$k_{18.2} = 2.5 \cdot (1.06)^{(18.2-20)} = 2.25\ \ /d$

b) Determine discharge values BOD using Equation 4 (Metcalf and Eddy, 2014):

$$S = \frac{s_0}{[1 + (k) \cdot SRT]} \quad (4)$$

$$S = \frac{200}{[1 + (2.25) \cdot 5]} = 16.32\ \ \mathrm{g/m^3}$$

2 - Estimate the concentration of biological solids according to Eq. 5 (Metcalf and Eddy, 2014):

$$X = \frac{Y \cdot (s_0 - s)}{[1 + (k_d) \cdot SRT]} \quad (5)$$

$$X = \frac{0.6 \cdot (200 - 16.32)}{[1 + (0.10) \cdot 5]} = 73.5\ g/m^3$$

An approximate estimate of biological solids produced is obtained by multiplying the assumed growth yield constant (BOD basis) by the removed BOD (Metcalf and Eddy, 2014).

3 - Estimate suspended solids in the lagoon effluent prior to settling (Metcalf and Eddy, 2014).

$$TSS = 200 + \frac{X}{0.85} = 200 + \frac{73.5}{0.85} = 286.47\ \mathrm{g}/m^3 \quad (6)$$

Estimate oxygen demand using equation 7 (Metcalf and Eddy, 2014).

$$R_0 = Q \cdot (S_0 - S) - 1.42 \cdot P_{x,bio} \quad (7)$$

a) Determine $P_{x,bio}$ the amount of biological solids wasted per day (Metcalf and Eddy, 2014).

$$P_x = X \cdot Q \cdot \frac{1\mathrm{kg}}{1000\ \mathrm{g}} \quad (8)$$

$$P_x\ = 73.5 \cdot\ 43200 \frac{m^3}{sec} \cdot \frac{1}{1000} = \ 3175.2\ kg/d$$

b) The conversion factor for BOD to COD is 1/1.6 for determining oxygen requirements (Metcalf and Eddy, 2014).

$$R_0 = \frac{43200 \cdot (200 - 16.32)}{0.625 \cdot 1000\ g/kg} - 1.42 \cdot 3175.2 = 8187.2\ kg/d$$

4 - Calculate ratio of oxygen needed to BOD removed by Eq. 9 (Metcalf and Eddy, 2014).

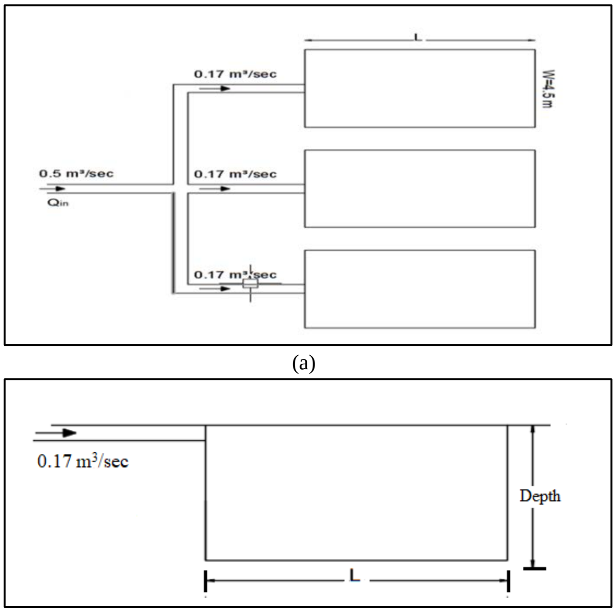
$$\frac{O_2 Required}{BOD\ removed} = \frac{R_o}{Q \cdot (S_o - S)\left(\frac{1kg}{1000g}\right)} \quad (9)$$

$$\frac{O_2 Required}{BOD\ removed} = \frac{8187.2}{43200 \cdot (200 - 16.32)\left(\frac{1kg}{1000g}\right)} = 1.03 \frac{kgO_2}{kgBOD}$$

5 - Determine the surface aerated energy requirements, the aerators used are valued at 1.8 kg O_2/kWh. (Metcalf and Eddy, 2014). The details of the design are shown in Fig. 1.

Aerated lagoons are an efficient and cost-effective system for primary and secondary treatment of wastewater in small communities. They integrate very well with the surrounding landscape.

When appropriate aerators are used, the energy input is similar to that of a comparable activated sludge system. In addition to providing adequate oxygen transfer, the aerators must provide mixing and circulation.



(a) (b)

Figure 1. Details of aerated lagoon (a) Plan and (b) Section

3.2.2. Oxidation ditch

An oxidation ditch is a modified biological activated sludge process that uses long residence times for solids (SRTs) to remove biodegradable organics. Oxidation ditches are classically complete mixed systems, but can be modified to approximate plug effluent conditions. Typical oxidation ditch treatment systems consist of single- or multi-channel configuration within an annular or oval basin. For this reason, oxidation ditches are also referred to as "racetrack" reactors, Figure 2.

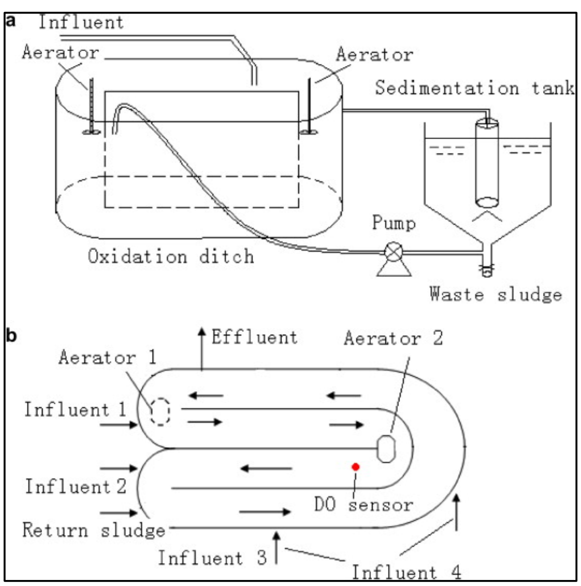


Figure 2. Schematic diagram of oxidation ditch (Liu et al., 2010)

Horizontally or vertically mounted aerators provide circulation, oxygen transfer, and aeration in the trench. The cross-sectional area of the trench is typically 1.2 m to 1.8 m deep and has 45° sloped sidewalls. Oxidation trench systems with a depth of 3 m or more with vertical sidewalls and vertical shaft aerators can also be used. Trenches can be made of a variety of materials, including concrete, asphalt, or impermeable membranes. Concrete is the most common. L-shaped and horseshoe-shaped structures have been built to maximize land usage (Davis, 2011).

i) Advantages

The main advantage of the oxidation ditch is its ability to meet separation performance objectives with low operational requirements, operating and maintenance costs. Specific advantages of oxidation ditches include (Xia and Liu, 2004):

a) An added measure of reliability and performance compared to other biological processes due to a constant water level and continuous discharge that lowers the weir above the discharge rate and eliminates the periodic surge of water common to other biological processes such as the Sequencing Batch Reactor.
b) Long hydraulic residence time and complete mixing minimize the influence of shock loading or hydraulic surge.
c) Compared to other biological treatment processes, less sludge is produced because biological activity is prolonged during the activated sludge process.
d) Energy-efficient operation results in lower energy costs compared to other biological treatment systems.

ii) Disadvantages

a) Compared to other modifications of the activated sludge process, the suspended solids concentrations in the Effluent are comparatively high.
b) This type of treatment requires a larger area compared to other activated sludge treatments. This can prove costly, limiting the feasibility of oxidation ditches in urban, suburban, or other areas where land acquisition costs are relatively high.

iii) Design criteria

Oxidation ditches are usually constructed of reinforced concrete, but asphalt, butyl rubber, and clay are also used.

Impervious materials are generally used to prevent erosion. The trenches are typically 1.2 m to 1.8 m deep and have 45-degree sloped or vertical sidewalls (Davis, 2011). The effluent enters the ditch after screening, is aerated, and circulates at a velocity of 0.25 to 0.35 m/s to keep solids in suspension (Metcalf and Eddy, 2014). The activated sludge recycle ratio ranges from 75 % to 150 %, and the suspended solids concentration in the mixed liquor (MLSS) ranges from 1500 mg/L to 5000 mg/L. The oxygen transfer capacity of oxidation ditches ranges from 2.5 to 3.5 lb/hp-h, 1.134 to 1.588 kg/hp-h (Process, 1999; Xia and Liu, 2004). The design criteria depend on the effluent content parameters and the required characteristics of the detergent, including the decision or requirement to provide a nitriding or denitriding effect and/or biological phosphorus removal. Specific design parameters for oxidation ditches include (Xia and Liu, 2004).

iv) Design procedure for oxidation ditch

Design an oxidation ditch for the treatment of the WW with the following parameters:

Average WW discharge= $\frac{m^3}{day}43200$ m^3/d (Measured from the site)
WW $BOD_5 = 4.85$ mg /L
WW SS = 400 mg /L
WW VSS = 200 mg /L
Total organic nitrogen concentration=30 mg/L
Total phosphorus concentration = 15 mg/L
Required effluent BOD_5 = 16.32 mg /L from Eq. 4
Required effluent SS≤ 10 mg/L (Davis, 2011)
Required underflow sludge concentration is 10,000 mg/L
WW temperature is 18.2 ˚C (Average temperature measured from the site)

The following parameters according to Wang et al. (2010):

1. Fraction of BOD synthesized, $a = 0.73$
2. Fraction of BOD oxidized for energy, $a' = 0.52$
3. Endogenous respiration rate, $b = 0.075\ 1/d$ and $b' = 0.15\ 1/d$
4. Fraction of BOD_5 synthesized to degradable solids, $a_o = 0.56$
5. No biodegradable fraction of VSS in influent, $f = 0.40$
6. Mixed liquor suspended solids (MLSS) = Xa = 6000 mg/L
7. Mixed liquor volatile suspended solids (MLVSS) = XV = 4200 mg/L
8. Temperature correction coefficient, $\theta = 1.02$
9. Degradable fraction of the MLVSS, $f' = 0.53$
10. Food-to-microorganism ratio, $F/M = 0.06$

6 - *Effluent soluble BOD_5, Se =10 mg/L*

Adjust the BOD removal rate constant for temperature:

$$k_T = k_{20}\theta^{(T-20)} \quad (10)$$

$k_{18.2} = 2.25\ 1/d$. calculated previously for design of aerated lagoon.

a) Determination the size of the tank according to Eq. 11.

$$V = \frac{a_0(s_0 - s_e)Q_{avg}}{X_V \cdot f'b} \quad (11)$$

Parameters were used from Wang et al. (2010). Where:

V is aeration tank volume, million galloon
a_0 is fraction of BOD_5 synthesized to degradable solids=0.56
s_0 is influent BOD_5, 200 mg/L
s_e is effluent soluble (BOD_5 = 16.32 mg/L), calculated from design of aerated lagoon;
Q_{avg} = Average waste flow = 0.5 m^3/s = 9.50 MGD
X_V is MLVSS and it is equal to 4200 mg/L
f' is degradable fraction of the MLVSS = 0.53
b is endogenous respiration rate, 0.075 1/d

$$V = \frac{0.56 \cdot (200 - 16.32) \cdot 9.50}{4200 \cdot 0.53 \cdot 0.075} = 5.85\ MG = 25768.57 m^3$$

Suppose depth of the tank is 1.5 m (1.2 m to 1.8 m) (Davis, 2011). Total surface area = 25768.57 m^3/1.5 m ≈ 17180 m^2. Calculation of detention time using Eq. 12.

$$t = \frac{V}{Q} \cdot 24$$

$$t = \frac{25768.57 m^3}{43200\ m^3 \cdot sec^{-1}} \cdot 24 = 14.3\ hour \quad (12)$$

Obtained time coincided with the criteria (6 to 30 hours) published by USEPA (2000). Determination of the oxygen requirements allowing 60 % for nitrification from Eq. 13:

$$O_2 = a's_rQ(8.34) + b'x_v \cdot V\ (8.34) + 0.6\ (4.57)(TKN)(Q)(8.34) \quad (13)$$

Where:

O_2= oxygen required, Ib/d
a' is fraction of BOD oxidized for energy = 0.56

s_r is BOD5 removed $= So - Se = 200 - 16.32 = 183.68\ mg/L$
Q is average waste flow 9.50 MGD = 0.5 m^3/s
b' is endogenous respiration rate, 0.15 1/d
x_v is MLVSS, 4200 mg/L
V is aeration tank volume, 5.85 MG = $25768.57 m^3$
TKN is total Kjeldahl nitrogen, 30 mg/L

$$O_2 = 0.56 \cdot 183.6 \cdot 9.50 \cdot (8.34) + 0.15 \cdot 4200 \cdot 5.85 \cdot \cdot (8.34) + 0.6\,(4.57) \cdot (30) \cdot (9.50) \cdot (8.34) = = 40309.3 \text{ Ib day}^{-1} = 18283.99092 \text{ kg/d}$$

Calculation of oxygen requirement per Ib BODr from Eq. 14; (it should be ≥ 1.5) Ib O_2/Ib BODr

$$= \frac{Q_2}{Q} \cdot S_r \cdot (8.34) \quad (14)$$
$$= \frac{40309.3}{9.5} \cdot 1.83 \cdot (8.34) = 2.8 \geq 1.5 \text{ OK.}$$

3.2.3. Wetland

Wetlands are typically used to treat wastewater and improve water quality for reuse. Wetlands use microorganisms, plants, and soil to treat wastewater. Plants such as sedges, cattails, reeds and bulrushes can grow in them as they can be filled with water up to 0.6 m deep. They mainly serve four functions, namely, landscape improvement, wastewater treatment, fish culture, and land aesthetics improvement. In some cases, constructed wetlands are the main and only wastewater treatment, in others they are just one step in a larger treatment process. Plants in constructed wetlands help philter wastewater and absorb solids, as well as transfer oxygen. Wetlands have many advantages, such as their good ability to remove pollutants (suspended solids and organic matter). In addition, wetlands do not require much energy or high maintenance costs and can be adapted to climate change (Vymazal, 2010).

There are several types of constructed wetlands: surface flow, subsurface flow, and hybrid systems that combine surface and subsurface flow. Constructed wetlands can also be combined with conventional treatment technologies, Figs. 3 and 4.

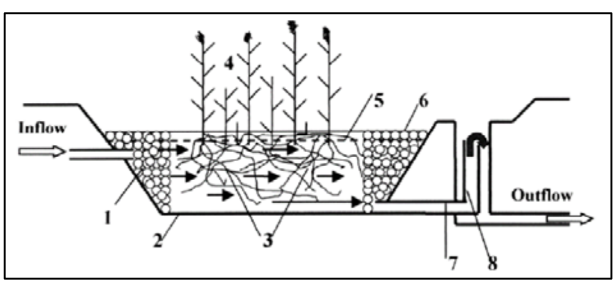


Figure 3. Schematic layout of a constructed wetland with horizontal subsurface flow. 1 inflow distribution zone filled with large stones; 2 impermeable layer; 3 filtration material; 4 vegetation; 5 water level in the bed; 6 outflow collection zone; 7 drainage pipe; 8 outflow structure with water level adjustment. (Vymazal, 2010)

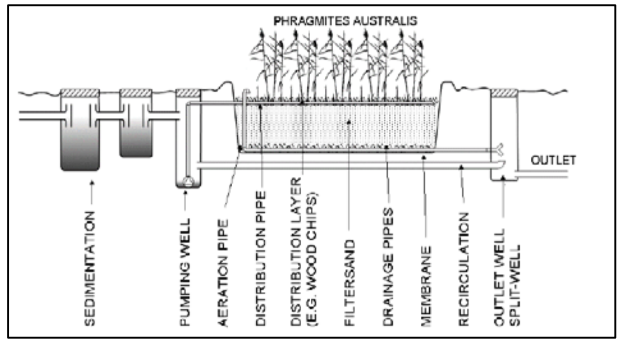


Figure 4. Layout of a vertical flow constructed wetland system for a single household (Vymazal, 2010)

Design procedure of wetland

BOD removal:

It is assumed that the removal of BOD follows first-order kinetics and that the continuous reactor formulation assumes complete mixing. Therefore, Eq. 7 is used as the kinetic model for the removal of BOD in the aerated lagoon, as shown in Eq. 15:

$$S_e = \frac{1}{1 + k_t} \cdot S_0 \quad (15)$$

where:

S_e is the outflow concentration, mg/L
S_0 is the inflow concentration, mg/L
k is the BOD coefficient at temperature T, 1/d
t is detention time, day.

$$S_e = \frac{1}{1 + 0.3} \cdot 200 = 153.85 \text{ mg/L}$$

Modification to temperature can be done using Eq. 3 (Zhang, 2012).

$$k_T = k_{20} \cdot \theta^{T-20}$$

where:

k_T is the BOD reaction coefficient at temperature T, 1/d
k_{20} is the BOD removal rate at 20 ˚C, 1/d
θ is the temperature coefficient 1.06

For normal sewage k_{20}= 0.3 1/d at 20 ºC (Shilton, 2006)

$$k_{18.2} = 0.3 \cdot \theta^{18.2-20} = 0.27 \text{ 1/d}$$

Area:
TKN surface area loading in wetland is 3 kg/ha. (Tousignant et al., 1999). Conservative estimates of effluent quality entering wetland:

TKN = 175 mg/L (Tousignant et al., 1999)

$$Daily\ TKN\ loading = 175\ \frac{mg}{L} \cdot Q\ \frac{m^3}{d} \cdot 10^{-3} = = 7560\ kg/d$$

$$Total\ surface\ area = \frac{(7560\ kg/d \cdot 10m^2/ha)}{\left(3\ \frac{kg}{ha} \cdot d\right)} = = 25200\ m^2$$

$$Wetland\ area = 50\%\ of\ 25200\ m^2 = 12600\ m^2$$

Designing two wetlands:

$$Area\ of\ each\ cell = \frac{12600\ m^2}{2} = 6300\ m^2$$

Overall size of wetland:
Aspect ratio: 4:1 (Tousignant et al., 1999). If width: 33 m then length: 132 m. Aspect ratio in the current design agree with the criteria mentioned by Wu et al. (2015).

3.3. Performance evaluation

The performances of aerated lagoons, oxidation ditches and wetlands for the treatment of wastewater from Erbil were studied. Parameters such as BOD5, COD, ammonia and TSS were used because they are widely used to study treatment methods (Renou et al., 2008; Abbas et al., 2009; Bashir, et al., 2015). In the literature, the values of BOD5, COD, ammonia and TSS for Erbil MWW were 13-110 mg/L, 20-188 mg/L, 3.25-11.4 mg/L and 200-400 mg/L, respectively (Mustafa and Sabir, 2001; Aziz, 2004; Aziz and Ali, 2017). BOD5, COD, ammonia and TSS parameters have been used in the study of wastewater treatment plants and the disposal standards due to their effect (EPA, 2003; Metcalf and Eddy, 2014; Bashir et al., 2015). Details of the inlet concentration, removal efficiency of the methods, outlet concentrations, and effluent standards are shown in Table 2. The results from Table 2 show that the common WWTP is the most efficient method for removing pollutants in the Erbil WWTP. Aziz (2020) studied the quality of wastewater of Erbil in the main sewer from 1994 to 2020 with possible treatment techniques and reuse. The results obtained in the present study are consistent with the work published by Aziz (2020). The removal of BOD5 and TSS in the aerated lagoons is in agreement with USEPA (2002).

3.4. Reusing Treated Municipal WW for Irrigation

The quality of untreated MWW and other types of WWs is different and it depends on the source of WW, for instance the quality of WW from dairy, steel, slaughterhouse, tannery, yeast, and paper factory are not the same (Aziz et al., 2019). Several treatment technologies are needed based on the pollutants in the WWs and should be treated to a level to qualify for the different types of irrigation, i.e. forest, greenbelt, wheat, fruits, vegetables, etc. (Mecalf and Eddy, 2014; Aziz and Ali, 2018; Aziz et al., 2019).

Table 2
Performance assessment for the Erbil MWW treatment using various techniques

Factors	Treatment Techniques			Discharge Standards
	Aerated lagoon	Oxidation ditch	Wetland	
Avg. inlet BOD (mg/L)	13-110 (61.5*)	13-110 (61.5*)	13-110 (61.5*)	40 mg/L (Iraqi Environmental Standard, 2011)
BOD removal (%)	70-95 (82.5*)	82-99 (90.5*)	90.8-92.3 (91.6*)	
Outlet BOD (mg/L)	10.76	5.84	5.17	
Inlet COD (mg/L)	20-188 (104*)	20-188 (104*)	20-188 (104*)	100 mg/L (Iraqi Environmental Standard, 2011)
COD removal (%)	62.5	61.5	89-91.7 (90.4*)	
Outlet COD (mg/L)	39	40	9.9	
Inlet ammonia (mg/L)	3.25-11.4 (7.3*)	3.25-11.4 (7.3*)	3.25-11.4 (7.3*)	1 mg/L (EPA, 2003)
Ammonia removal (%)	≈ 90	90-94 (92*)	83.8-87.5** (85.7*)	
Outlet ammonia (mg/L)	0.71	0.584	1	
Inlet TSS (mg/L)	200-400 (300*)	200-400 (300*)	200-400 (300*)	35 mg/L (EPA, 2003)
TSS removal (%)	60.3	69-97 (83*)	90.4-93.2 (91.8*)	
Outlet TSS (mg/L)	119.1	51	24.6	
References	INDITEX (2015)	USEPA (2000); Hadisoebroto et al. (2014)	Gikas and Tsihrintzis (2014)	

* Average Value
** Removal efficiency for NH4-N

Three key views should be measured for irrigation by treated WW, which cares about public health for farmers and users, the avoidance of atmosphere degradation, and removes the antagonistic that has an effect on the production of crops. Various organizations for using TWW for irrigation concentrated on, the amount of indicator organisms, biodegradable organic matter, TSS, turbidity, heavy metals, and residual chlorine that has an effect on public health (Paranychianakis, et al., 2011; Aziz et al., 2019).

In this study and based on the pH, EC, and TDS results, there are no limitations to the use of MWW (Aziz et al., 2019). The MWW is considered as water with medium salinity (Punmia and Lal, 1979). According to EC and chloride values, Erbil water is considered completely safe for irrigation (Abbas, 1986). The obtained results are in agreement with the data published by Aziz et al. (2019). Of course, treatment of wastewater from Erbil with different techniques reduces pollutants such as organic matter, TSS, nitrogen compounds, etc. in wastewater (USEPA, 2000; Gikas and Tsihrintzis, 2014; Hadisoebroto et al., 2014; GINDITEX, 2015). Consequently, treatment of wastewater improves the quality of Erbil's wastewater and it can be used for irrigation purposes.

4. Conclusions

The results showed that the wastewater from Erbil is considered to be low polluted and some quality parameters exceed the standards for wastewater disposal. The total planned area for aerated lagoons, oxidation ditches and wetlands were 72000 m^2, 17180 m^2 and 25200 m^2, respectively. The wetland design resulted in 91.6 % reduction in BOD5, COD, ammonia, and TSS. 90.4 %, 85.7 % and 91.8 %, respectively. Compared to the aerated lagoon and oxidation ditch methods, the wetland method was generally the most effective. Based on the above treatment methods, the treated wastewater can be reused for irrigation, and the wastewater has medium salinity and is completely safe for irrigation. In this way, drinking water is no longer used for irrigation in the city of Erbil.

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Postupak osmišljavanja i izvođenja metoda aerisane lagune, oksidacionog jarka i konstruisanja mokrih polja za tretman i ponovnu upotrebu otpadnih voda u Erbilu

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INFORMACIJE O RADU

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Ključne reči:
Aerisane lagune
Navodnjavanje
Oksidacioni jarak
Otpadne vode
Mokra polja

I Z V O D

Cilj ovog istraživanja je bio ispitivanje karakterizacije, tehnike tretmana i ponovna upotreba sveže komunalne otpadne vode iz jugoistočne oblasti grada Erbila koji se nalazi u oblasti Kurdistan u Iraku. Prikupljeni uzorci otpadnih voda analizirani su na 21 parametar kvaliteta. Neki od parametara kao što su boja (146 Pt. Co i 337 Pt. Co), ukupne čvrste materije (800 mg/L), suspendovane čvrste supstance (400 mg/L i 1100 mg/L), nitrati (17,7 mg/L), nitriti (11 mg/L i 29 mg/L), i amonijak (2,09 mg/L i 2,64 mg/L), premašili su standarde za odlaganje otpadnih voda. Shodno tome, bilo je potrebno sprovesti tretman pre nego što se otpadna voda ispusti u prirodno okuženje. Dizajnirane su tehnike za tretman kao što su earisane lagune, oksidacioni jarak i konstruisanje mokrih polja. Objašnjene su procedure osmišljavanja, proračuni i performanse za svaku metodu tretmana. Ukupna površina projektovana za aerisane lagune, oksidacioni jarak i mokra polja, iznosila je 72 000 m^2, 17 180 m^2 i 25 200 m^2. Metoda konstruisanja mokrih polja je bila najefikasnija metoda sa efikasnošću od 91,6 % za biohemijsku potrebu za kiseonikom, 90,4 % za hemijsku potrebu za kiseonikom, 85,7 % za amonijak i 91,8 % za suspendovane čvrste materije. Prečišćena otpadna voda može se ponovo koristiti za navodnjavanje i potpuno je bezbedna. Korišćenje prečišćenih otpadnih voda iz jugoistočnog dela Erbila za navodnjavanje umesto vode za piće predstavlja ekonomično rešenje i doprinosi očuvanju izvora pijaće vode.

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Proposition of Waste Glass Containers Usage as Secondary Raw Material for Clay Blocks Production

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ABSTRACT

The main objective of the present study was to propose the feasible usage of secondary raw material obtained from waste glass containers in the manufacture of clay blocks, driven by environmental benefits. Main goals were to reach a high content of waste glass in clay blocks, to use very low firing temperature and still obtain products with suitable physical and mechanical properties. Blocks with 10 wt. %, 20 wt. %, and 30 wt. % of waste glass in content were experimentally produced with the firing temperature of 880 °C. Relevant physical and mechanical properties were measured and their dependence on waste glass content was determined. Material flow analysis (MFA) showed that utilization of waste glass in clay block production can generate positive environmental impacts including landfill lifespan extension and contribution to the waste glass recycling.

1. Introduction

Municipal solid waste (MSW) management represents a growing problem in countries worldwide due to increased production and consumption. Countries with developed economies have state-of-the-art waste technology treatments, such as controlled landfills, incineration, anaerobic digestion, modern recycling facilities, and carefully developed programs of waste selection in households. Lower-income countries generally rely on open dumping, uncontrolled, controlled, and sanitary landfills.

Improvements in living standards and technological development have brought about a significant growth in the consumption of single-use bottles. Despite glass being 100 % recyclable, which can provide significant environmental benefits, such as reduction of energy and natural resources consumption, only small portion of glass containers waste is covered by recycling programs based on primary selection, while all other glass waste is being collected within mixed municipal solid waste. Recent results showed (Topcu and Canbaz, 2004; Turgut, 2008; Demir, 2009) that unlike other waste products, glass is imperishable and thus detrimental to the environment.

The nature and dimension of waste-related impacts on the environment depend upon the amount and composition of waste streams, as well as on the method of treating them. Waste glass from waste glass containers is a waste material which has potential for recycling as a

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brick additive, as a fine aggregate in concrete and in ceramic tile production (usually in porcelain stoneware tile). In this manuscript, the use of recycled glass as a brick additive will be considered based on the previously reported fact (Chidiac and Federico, 2007; Loryuenyong et al., 2009; Andreola et al., 2016) that its use in brick production has a potential for improvement in both structural and durability properties. According to the reviewed literature, the percentage addition of waste glass in the bricks samples and ceramic tiles was done in the range of 0.5 wt. % to 94 wt. % of waste glass. Most of the research dealt with the tests of samples with waste glass in the range between 5 wt. % and 20 wt. % and the size of glass particles between 45 µm and 600 µm in bricks production with glass. In the available test samples results, it was observed that as the mass percentage of glass in the samples increases, the activation energy of the sintering process decreases, while the viscosity of the liquid phase in the waste glass sample decreases with additional glass (Matteucci et al., 2002; Hwang et al., 2006; Chidiac and Federico, 2007; Lin, 2007; Luz and Ribeiro, 2007; Raimondo et al., 2007; Demir, 2009; Loryuenyong et al., 2009; Mustafi et al., 2011; Phonphuak et al., 2016).

By reviewing the obtained research results in this area of waste glass application, it can be concluded that the percentage of glass addition directly affects the mechanical properties of bricks, porosity, and water absorption of bricks, as if the grain size of recycled glass has an effect on the properties of the samples. Moreover, it has been recently published (Phonphuak et al., 2016) that the waste glass content of 10 wt. % in clay bricks could be used as a potential fluxing agent to help lowering firing temperature down to 900 °C; a lower firing temperature of 900 °C was used in conjunction with the incorporation of 10 wt. % waste glass to produce bricks with similar or better physical properties to normal brick fired at 1000 °C. Based on the results of Loryuenyong et al. (2009), with the firing temperature of 1100 °C, wasted glass addition up to 30 wt. % did not cause detrimental effects to the properties of clay bricks, and clay bricks prepared with 15–30 wt. % were able to meet the minimum requirements in a wide range of applications and even in some load-bearing structures.

In this study it was investigated how the addition of the powder obtained from waste glass containers into clay blocks, influences the relevant properties, when the lowest possible firing temperature is used and what are the environmental benefits.

The optimum firing temperature that is in use in industrial brickyards depends on the clay properties, but the lowest temperature used in practice to produce blocks with required properties is 880 °C. In this study, blocks with up to 30 wt. % of waste glass in content were experimentally produced with the firing temperature of 880 °C. Relevant properties of the blocks were measured and compared with standards. In order to evaluate the potential environmental benefits of proposed usage of waste glass containers, material flow analysis (MFA) was used, on an example of a landfill in Serbia.

2. Material and Methods

2.1. Preparation of the raw materials and specimens

It is well known that characteristics of powders depend on the type of material, but also on the grain size of powder. Consequently, characteristics of a material obtained from powders, depend on those factors and determine a final application of a product obtained from a secondary raw material. In order to investigate the possibility to reuse waste glass containers glass as secondary raw materials for block production, powder preparation and its sieve separation was done.

The waste glass was crushed using a ball mill. The particle-size distribution test was carried out for the waste glass using sieve size analysis according to the Tyler scale (by a factor of $2^{1/2}$ geometrical progression and basic sieve with 200 Mesh). Figure 1 shows the results of particle-size distribution test, for a representative sample.

The clay used in this study was typical clay from Vojvodina province, regularly in use in the local brickyards.

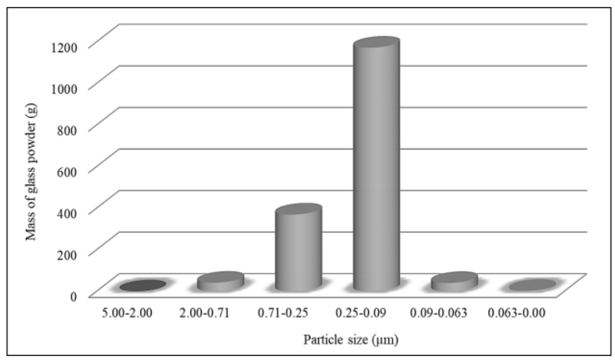

Figure 1. Particle size analysis of powder obtained from the waste glass containers

Optimizing of the grinding regime enabled obtaining of the glass powder with uniform particle size, with insignificant mass losses in the processes of grinding and sieve size analysis. The highest percentage of the obtained particles had a size below 0.71 µm, which was a suitable size for block production. After optimization, a greater amount of waste glass containers was processed according to the selected mode of preparation, grinding and sieve separation in order to obtain fine-grained secondary raw material.

Raw materials (clay and waste glass powder) were mixed until homogenous mixture was obtained. 20-25 wt. % of water was added and mixed to obtain plastic condition of mixture. Experimental soft mud rectangular clay blocks with dimension of 40 mm x 25 mm x 40 mm were formed using a block extruder. The block specimens

Figure 2. Phases of obtaining experimental clay blocks with waste glass

were air-dried at room temperature (20-25 °C) for 24 h, and then over dried at a temperature of 50 °C, 70 °C, and 105 °C, successively, for another 24 h to remove water content. The green specimens were fired at temperatures of 880 °C for 2 hours (Vimselectric furnace). Heating and cooling rates were set at 1 °C/min. Figure 2 shows phases of the obtained clay blocks.

2.2. Experimental determination of the relevant clay blocks properties

The investigated and reported physical and mechanical properties were structural analysis, water absorption, bulk density, and compressive strength.

Qualitative determination of major crystalline phases present in the clay materials and quantitative changes in quartz content were achieved by using the X-ray diffraction. The X-ray diffraction (XRD) was carried out using Philips PW 1050 instrument, with Cu Kα1,2 radiation, and a step scan mode of 0.03° in angular range 2θ=5-70°.

Archimedes method was used to determine the water absorption and bulk density.

The measurement of compressive strength was carried out on 5 samples from each category of samples divided by the content of the glass powder (0 wt. %, 10 wt. %, 20 wt. %, and 30 wt. %). The average value of strength for each sample type was considered as representative.

Before the measurements, the samples were prepared by filling their cavities with Styrofoam applying a thin layer of mortar to flat out the edges and surfaces on which the pressure was to be applied. The test for compressive strength was carried out on a press (ZRMK Ljubljana, Slovenia), within a measuring range from 150 to 400 kN.

A static load was applied, with incremental workforce of approximately 0.3 MP/s (short-term static loading).

2.3. Tools for estimation of environmental benefits. Indicators for scenario evaluation

In order to estimate potential financial and environmental implications of waste glass containers usage in clay block production, the Novi Sad waste management region was analysed as a case study area.

The total amount of generated waste glass containers that represent the input flows into analyzed waste management system during time period of one year was 9,000 tons, as reported in Waste Management Strategy for the period 2010-2019.

Two scenarios were modeled using MFA software STAN, following the models published by Cencic and Rechberger (2008).

Scenario 1 represented the current practice of waste management in Novi Sad region, where all amount of glass waste, due to the lack of demand for the recycling, was disposed in landfill, and Scenario 2 as more advanced waste management system with separate collection of recyclables from households in dry waste bin, and more significant utilization of waste materials assumed that 70 % of generated waste glass would be selected, crushed and used for the clay block production.

Although the previous case study of block manufacturing and the use of waste glass cullet, made by Hodge et al. (2010), was focused on the potential economic value of this recycling, it demonstrated that waste glass recycling for block manufacturing could bring novel profits and associated reductions in environmental impacts.

Hence, energy, climate impact (CO_2 emissions), landfill lifespan extension, and costs were used to evaluate potential usage of waste glass for block production and compare alternative with current practice.

2.3.1. Energy consumption reductions

Various Life Cycle Assessment (LCA) studies of building products have shown that energy consumption should be the focus of reducing the environmental impact of structural clay manufacturing. This idea is strengthened by atmospheric emissions of CO_2 for fossil fuels combustion and total suspended solids quantities. Based on two various studies made by EPA (2016, 2018) which have aggregated multiple facilities that use different sources of energy, the average energy consumption per 1 kg of finished clay product is 4.123 MJ. This heat is obtained from the combustion of fossil fuels, mostly of natural gas. These calculations are based on the technological process in which the block must be fired at 1,000 degrees Celsius for more than 24 hours.

2.3.2. Climate impact

In accordance with EPA carbon dioxide emissions (CO_2) of natural gas combustion, production of 1 kg of finished clay product produces 0.207 kg of CO_2, while production of 1 kg of finished clay product with 30 wt. % of waste glass produces 0.182 kg of CO_2.

2.3.3. Impact on the landfill`s lifespan

Glass as imperishable material, although it does not produce particular pollution, after the disposal in landfill it tends to remain permanently which has direct impact on landfill's lifespan and indirectly on financial aspects of the landfill. By avoidance of glass disposal in landfill, besides potential profit from sale of glass as recyclable material, there is a benefit of lower costs for the landfill tax, due to the less amount of waste, which is in this case 0.035 €/kg. Based on data released by EPA (2016) on density of semi crushed glass bottles, 1,068 kg/m^3, average density of mixed MSW in landfill 800 kg/m^3, data on total waste generation rate 189,089 t/year and the data on waste glass container amount which can be selected and used in clay block production 5,587 t/year, landfill space savings and landfill`s lifespan extension will be calculated.

3. Results and Discussions

3.1. X-ray diffraction analysis

Mineralogical composition of obtained clay blocks and blocks with waste glass was carried out using X-ray diffraction analysis. X-ray diffractograms are shown in Figures 3 and 4.

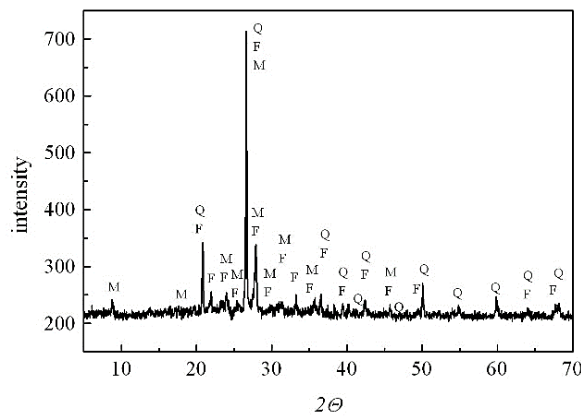

Figure 3. X-ray diffractogram of block with 10 wt. % of glass in composition. Q-quartz, F-feldspare (albite/ anorthite and/or orthoclase), M-muscovite (mica group)

In Figure 4 the following diffraction curves are shown: 1: 0 wt. % of glass, 2: 10 wt. % of glass, 3: 20 wt. % of glass, 4: 30 wt. % of glass. Clay blocks contained quartz, feldspare (albite/ anorthite and/or orthoclase) and muscovite (mica group). Since the X-ray diffraction measurements were conducted under the same conditions, comparison of the peak areas with the most intense line of quartz (2Q=26.600; d=3.35 Å) was done for the X ray diffractograms of block with a different content of glass in the composition of blocks. It was confirmed that the increase of glass share in the blocks caused decreases of this line area, which was a confirmation of the decline of the mass concentrations of quartz in the blocks.

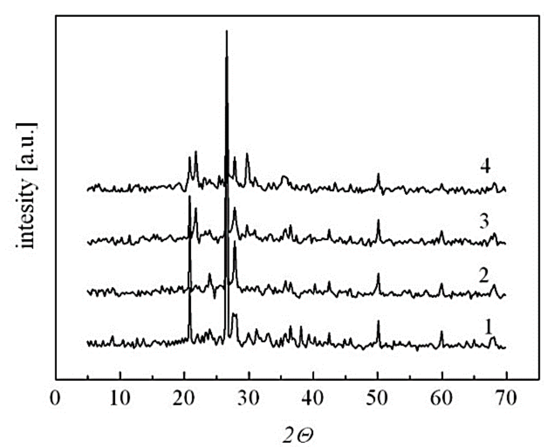

Figure 4. X-ray diffractograms of blocks with different glass content in composition. 1: 0 wt. % of glass, 2: 10 wt. % of glass, 3: 20 wt. % of glass, 4: 30 wt. % of glass

3.2. Water absorption

Water absorption is an important factor for the durability of clay products. When water infiltrates brick, it decreases the durability of brick. Thus, the internal structure of block must be sufficiently dense to void the intrusion of water.

As it can be seen in Figure 5, water absorption of blocks was in the range of 14.4 wt. % and 17.3 wt. % depending on waste glass content.

According to ASTM C62-13a (2013), the Grade MW and SW blocks must have an average maximum absorption of 22.0 and 17.0 %, respectively. While regular clay blocks meet the required average maximum absorption for Grade MW, block with waste glass in composition meet both the Grade MW and SW.

3.3. Density

The bulk density is a very important quality for clay bricks, since it is related to its durability and water absorption.

As the density of a clay bricks increases, its strength also increases, while its water absorption decreases.

The densities of blocks containing waste glass were in the range of 1.69970 g/cm^3 to 1.76784 g/cm^3 (Figure 6), depending on the waste glass content.

3.4. Compressive strength

Compressive strength is the most important engineering-quality index for building materials and it is a mechanical property used in clay block specification. In this study the result indicated that the strength of fired clay blocks greatly depended on the amount of waste glass addition. The results revealed that the compressive strengths were in the ranges of 21.79 MPa to 35.59 MPa when waste glass addition increased from 0 wt. % to 30 wt. %. As it has been previously published by Phonphuak (2016), the addition of waste glass considerably contributed to vitrification and enhanced the strength development by closing the internal pores with glassy phase, especially during firing. According to the standard ASTM C62-13a (2013), the Grade MW blocks must have an average minimum compressive strength of 17.2 MPa; all the blocks prepared in this research met this standard. Results of the compressive strength measurements of clay blocks with waste glass (0 wt. %, 10 wt. %, 20 wt. % and 30 wt. % of glass in composition), are shown in Figure 7.

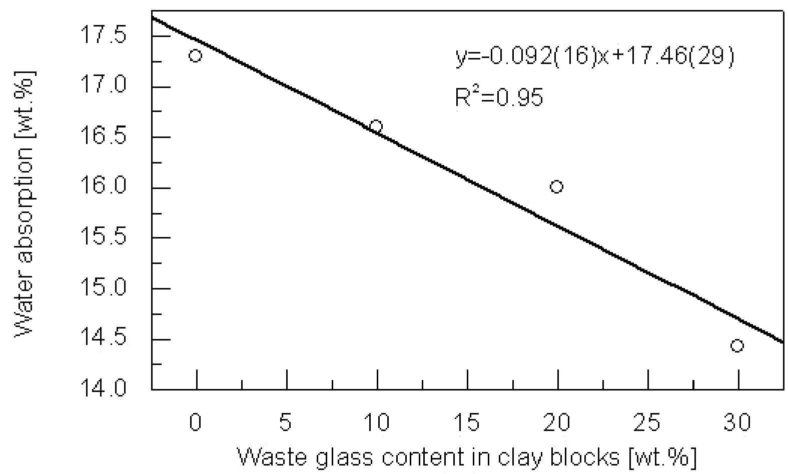

Figure 5. Water absorption dependence on waste glass content in clay blocks

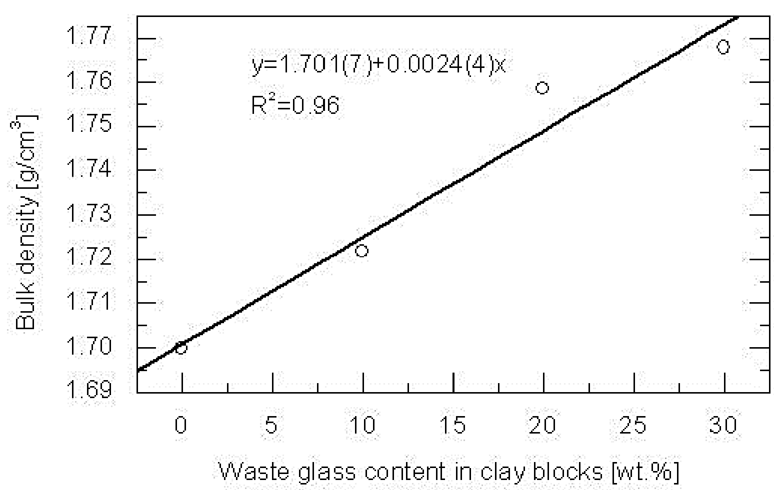

Figure 6. Bulk density dependence on waste glass content in clay blocks

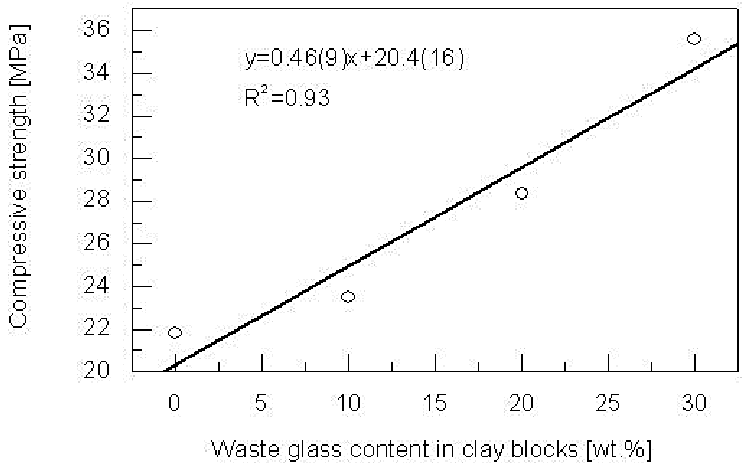

Figure 7. Compressive strength dependence on waste glass content in clay blocks

The average compressive strength of investigated clay blocks with waste were in the range of 21.79 MPa and 35.59 MPa, depending on the waste glass content.

3.5. Scenario modeling results

New forms of waste recycling can bring novel insight into the relationship between potential profits and associated reductions in the environmental impacts. Identifying any potential recycling that can be economically and environmentally attractive is of a great importance and some positive analysis was already reported for the brick industry (EPA, 2018). More than 20 % of waste glass containers are transported to the separation facility, while the rest of 7,000 tons are directly landfilled without any pre-treatment. As shown in Figure 8, most of the glass containers end up in landfill while a very small amount is recycled. Figure 9, which presents Scenario 2, shows one of the few possible ways to reduce the amount of deposited glass containers to the landfill by using waste glass in blocks production. The proposed waste collection system projects that the glass containers are collected in a bin with other recyclable containers (so called "dry bin"). In Scenario 2, available amount of waste glass containers, after passing through the Separation plant instead of being disposed in landfill, as shown in Scenario 1, would be sent to a glass crushing plant, in order to obtain processed glass cullet. Within the Scenario 2, about 60 % less of waste glass containers will end up on the landfill. The amount of 5,587 tons of processed glass cullet could be used for making 17,948 tons of fired blocks with share of 30 wt. % of glass.

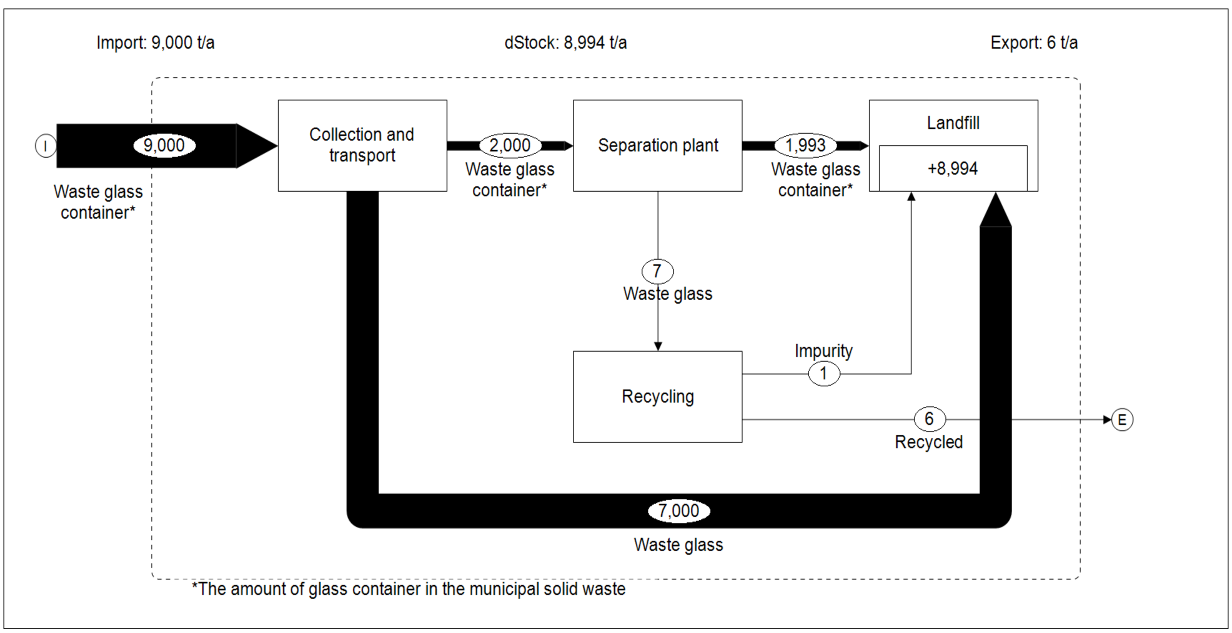

Figure 8. Scenario 1 - Current situation of waste glass containers deposited at the landfill in Novi Sad region as a potential source for block production

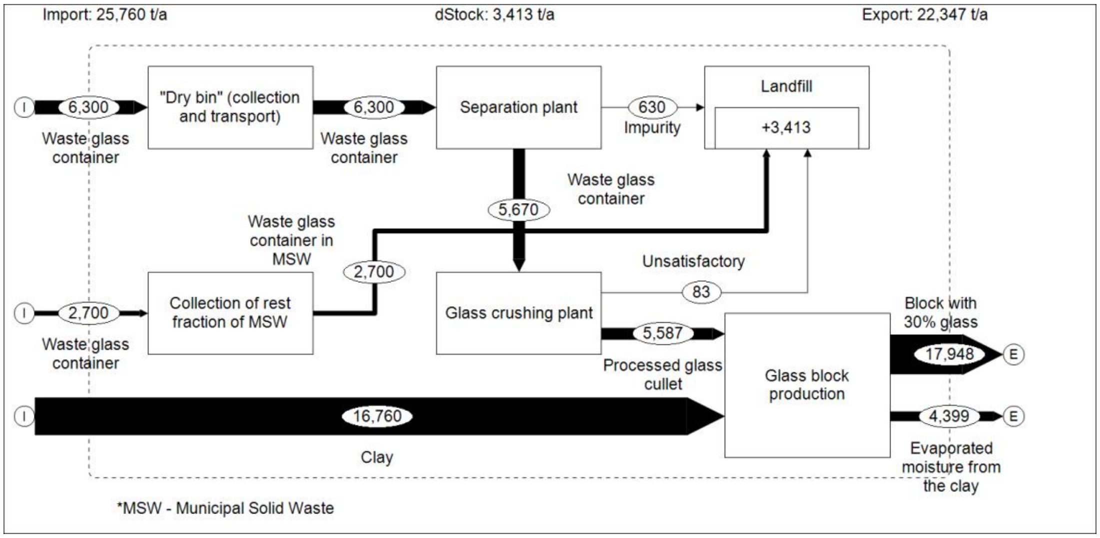

Figure 9. Scenario 2 - Using 30 wt. % of glass cullet from landfill in Novi Sad as a share of raw material for block production

The results demonstrated that the addition up to 30 wt. % of waste glass and lowering the firing temperature down to 880 degrees Celsius did not cause detrimental effects to the properties of clay blocks. Based on the previous data, it can be estimated that the application of the proposed waste glass usage would lead to the average energy saving of 0.495 MJ per 1 kg of finished block. The amount of the block production of 17,948,000 kg per year (the amount needed for consumption of all available waste glass from landfill in Novi Sad) could result in energy saving of 8.884 TJ per year. Considering that raw clay has larger specific heat capacity than glass cullet (up to 50 %, depending on the clay composition, water content and glass composition), this reduction in heat consumption would be even larger in practice, due to the lower heat consumption during the heating to the plateau of firing. Considering the annual block production of 17,948,000 kg with the share of 30 % of waste glass, savings in CO_2 emissions would be around 446,823 kg of CO_2 per year.

Taking into account that density for semi crushed glass bottles is 1,068 kg/m^3 (EPA, 2016) and that the 5,587,000 kg per year of waste glass containers would be used in the block production, instead of disposal in landfill in Novi Sad, around 5,231 m^3 per year of space for waste disposal in the landfill could be saved. How the annual production of municipal waste in Novi Sad region is about 189,089 tons, and the average density of landfilled municipal solid waste is 800 kg/m^3 (EPA, 2016), space that is annually required for municipal waste disposal in the landfill is 236,361 m^3 (Scenario 1). In this case, the use of waste glass containers in block production would result in saving space for municipal waste disposal in the amount of about 2.2 %. As the landfill lifetime is about 20 years, use of waste glass containers in the block production as stated in Scenario 2 would extend the landfill lifetime for 161 days, which represents a certain benefit considering the share of glass in municipal waste.

As a result of socio-economic growth, major increase in glass waste generation is taking place which can lead to resource depletion and environmental concerns. Considering concept of the circular economy, which is to transform waste into a valuable resource by designing the product to be easily reparable, recoverable, and used as primary or secondary material for the same industry (closed-loop) or another industry (open-loop), the use of waste glass as a secondary resource in the production of clay blocks, described in this manuscript, is an ideal example for implementing a circular economy. The obtained results indicate the possibility of connection construction sector and circular economy with recycled glass in its center.

4. Conclusions

Waste glass containers can be used as secondary raw materials for obtaining a new product - clay blocks. Research of a relevant properties have shown that the clay blocks with waste glass meet the usual requirements by standards and that the proposed technology can be applied in practice for the production of clay blocks with 30 wt. % of glass and the firing temperature of 880 °C.

Results of environmental benefits and economic impact of waste glass usage for clay blocks production analysis indicate that proposed utilization generates positive economic impact due to the landfill lifespan extension.

These effects can be of a great importance for developing parts of the world where rudimentary waste management methods are currently applied and the proposed process can be an important improvement in waste management and environmental protection.

Acknowledgement

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Predlog upotrebe otpadne staklene ambalaže kao sekundarne sirovine u proizvodnji blokova od gline

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Reciklaža
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I Z V O D

Osnovni cilj ove studije bio je da se predloži izvodljiva upotreba otpadne staklene ambalaže kao sekundarne sirovine u proizvodnji blokova od gline, sa akcentom na benefite po životnu sredinu. Osnovni ciljevi su bili upotreba visokog sadržaja otpadnog stakla u blokovima od gline, korišćenje veoma niske temperature pečenja i dalje dobijanje proizvoda sa odgovarajućim fizičko-mehaničkim svojstvima. Proizvedeni su eksperimentalni blokovi sa 10 %, 20 % i 30 % mase otpadnog stakla pri temperaturi pečenja od 880 °C. Ispitana su relevantna fizičko-mehanička svojstva i utvrđena je njihova zavisnost od masenog procentualnog udela otpadnog stakla prisutnog u eksperimentalnim blokovima. Primenom metode MFA (Analiza tokova materijala) utvrđeno je da se upotrebom otpadnog stakla u proizvodnji blokova od gline pozitivno utiče na zaštitu životne sredine, uzimajući u obzir produženje životnog veka deponije i poboljšanje reciklaže otpadnog stakla.

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Dissolved Air Flotation (DAF) Operational Parameters and Limitations for Wastewaters Treatment with Cost Study

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ABSTRACT

Dissolved air flotation (DAF) technology is one of the efficient techniques for purification of many types of wastewaters which contain pollutants less dense than water. Nowadays, due to high quality standards, wastewaters should be treated with high quality wastewater treatment techniques which meet the appropriate standards. DAF can remove suspended materials and oily particles contained in raw wastewaters. The study aims to review DAF system with its operation and limitations of the system. Additionally, the cost of system is discussed. Pre-treatments of primary sedimentation and post treatments such as filtration, biological, and chemical treatments can enhance the removal of pollutants and efficiency of the system.

1. Introduction

Increasing industrialization and urbanization have great impact on consuming large quantities of water resulting in generating excess wastewaters in domestic and industrial sectors (Varjani et al., 2019). Disposing and directly discharging wastewaters into the water bodies without proper treatment is alarming and has great effect to natural water and environment. This work aims to investigate the use of Dissolved Air Flotation (DAF) technology for treatment of wastewaters. Moreover, the operation parameters and performance of DAF, as well as pre and post treatment of DAF process are explained and reviewed. Nowadays, DAF technology has been widely used in many industries to treat various types of wastewaters, such as oil refineries, paper making, laundries, car washings, metal processing, and many other industries. The DAF process consists of four basic steps including:

- Generating bubbles in the wastewater;
- Contact between the gas bubble and the suspended particles in wastewater;
- Attachment of the suspended particles to the gas bubbles;
- Rising of the air/solids combination to the surface where the floated material is skimmed off (Shammas et al., 2010).

2. DAF and functions for wastewaters treatment

The main objective of air flotation process, is an efficient way to separate light particulates and oils from wastewater. Particles that adhere to air bubbles can float from the liquid phase. DAF is also separation process between oil and water droplets. Removals is accomplished by dissolving the air in water or wastewater under pressure of 40 psi to 80 psi and then releasing the air under atmospheric pressure in the

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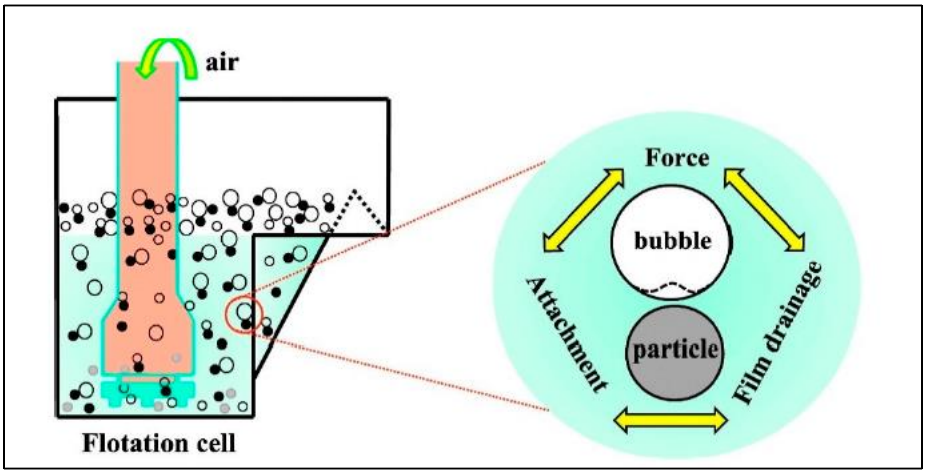

Figure 1. Principle and concept of DAF (Abuhasel et al., 2021)

flotation tank. When the pressure is reduced in DAF tank, the result is the formation of micro bubbles ranging in size between 20-100 μm. Small bubbles move upward to the surface and become entrapped by oil particles and organic matters, and are consequently removed with the froth (Al-Shamrani et al., 2002; Shammas et al., 2010), Figure 1.

Many methods and techniques used for water and wastewater treatment, among them DAF, have become the more advanced efficient techniques for reducing impurities and suspended particles inside the wastewater.

Jung et al. (2016) used the DAF technique for drinking water applications and reported that DAF had a sufficient impact on reducing algal load since algae were characterized by the tendency to float, low cell density, its small size, and negative surface charges. According to Teixeira and Rosa (2006), comparison was made between DAF and conventional sedimentation technique for the treatment of algae rich water. It was recorded that generally DAF technique could be considered more effective than sedimentation. However, the dose and type of coagulant, as well as the coagulation, flocculation and DAF operating conditions were key parameters for removing bacteria cells. Yu et al. (2017) recorded that DAF could remove 90 % of oil and 92.5 % of chemical oxygen demand (COD) in the treatment of oily wastewaters.

3. Performance of DAF and influencing factors

The effectiveness of the process mainly depends on how well the particles can be agglomerated with air bubbles in order to achieve maximum collision and attachment between air bubbles and the suspended particles. In addition, bubbles must rise under laminar flow conditions. This avoids shredding of flocs, which can occur in a turbulent regime. The maximum bubble size for laminar flow is 130 μm (AWWA, 1999). The main factors involved in the DAF process are air pressure, recycle ratio, and air to solid ratio. The size of the bubbles is an important factor to achieve an efficient solid-liquid separation during their float to the surface (Torrealba, 2007).

3.1. Air pressure

Bubble generation and size of bubbles in wastewater depends on the air pressure which has been pressurized into the DAF tank. Typical value of operational parameter for air pressure ranges between 40-80 psi (Torrealba, 2007). In DAF system, there are two methods for generating bubbles in DAF unit. Wastewater is pressurized through air diffuser or air nozzle discharged from the bottom of flotation tank. Or the wastewater is aerated with air until it is saturated at atmospheric pressure (Tang and Liu, 2006).

3.2. Recycle ratio

The recycle ratio is the fraction or part of treated wastewater when the final effluent is returned to the pressurization DAF tank. The recycle ratio helps the DAF unit to avoid flocs and agglomerated particles to disruption with generated bubbles. The portion can vary typically between 15-50 % or 20-100 % for water and wastewater applications, respectively (Tang and Liu, 2006; Srinivasan, 2009). Rattanapan et al. (2011) used 20-40 % recycle ratio for the treatment of biodiesel wastewater by DAF with alum and acidification. Recorded removal efficiency of COD was 85-95 %.

3.3. Air to solid ratio (A:S)

This parameter refers to the amount of air needed to float solid particles to the surface of floatation tank. The higher air/solid ratio causes higher turbulence of water and results in breaking the bond between solid particles and bubbles. Typically for low influent concentration, the system starts with low A:S ratio, between 0.005 and 0.010 (Ross et al., 2000).

4. Operational parameters of DAF unit

4.1. Hydraulic Retention time (HRT)

One of the most important parameter in designing DAF system is the time of remaining wastewater in the tank, i.e. flotation time that has impact on the performance and optimization of the operation parameters of the DAF system.

Typically, HRT for DAF ranges from 20-60 minutes. However, when treating high flow and high flow effluents, the longer flotation time will be used.

HRT decreases by increasing flow rate, which results in decreasing bubble production and longer time needed for air to dissolve totally inside the reactor (Dassey and Theegala, 2012).

Alshahri et al. (2021) evaluated three flotation times 5, 10, and 15 min. Thereby, it was found that 10 min of flotation time was effective at improving the raw water quality. Results indicate there is an optimum flotation time which is a function of the feed water quality, type and dose of coagulant, where further studies are required to identify this value. Table 1 shows different HRT with operating conditions for DAF system.

Table 1
HRT with operating conditions for DAF system

No.	Wastewater type	Treatment technique	Operation conditions	HRT	Removal (%)	Reference
1	Urban wastewater	Chemical coagulant + DAF	FOG: 57 mg/l	4 months	FOG: 74	Collin et al. (2020)
2	Biodiesel wastewater	DAF by acidification and coagulation	pH:3 , 1 g/l alum, chloride and ferric chloride recycle rate: 20-30 %	1 d	Oil and grease 85-95	Rattanapan et al. (2011)
3	Raw water	DAF and GAC	Loading rate: 20-40 $m^3/m^2.h$ Q: 500 m^3/d	-	Turbidity: 98	Jung et al. (2016)
4	Raw water	High rate DAF and filtration	Cold water 3-5 ºC Loading rate 30-40 m/h Flocculation time: 5min	-	Good turbidity removal	Edzwald et al. (1999)
5	Car wash wastewater	Hybrid process; coagulation-flocculation and DAF	Ferric chloride, Alum and quick lime coagulants, Pressure:1,3 and 5 bar	1-5 h	COD: 92 Turbidity: 98	Golestani and Fathali (2015)
6	Municipal wastewater	DAF	10mg/l Poly aluminum chloride, 22 % Recycle ratio, Flocculation time G-value 55 S^{-1}	8 min	Total phosphorus:90 COD:47 TSS:77	Koivunen and Heinonen (2008)
7	Coal mining wastewater	Coagulation, flocculation and DAF	Coagulant 50mg/l Flocculants: 0.5 mg/l Air pressure 4.5 bar Recycle ratio 30 %	5 min	Turbidity: up to 98 %	Couto et al. (2011)

5. Improvements for DAF

Industries that discharges their effluents into rivers, lakes, and environment have used DAF for many years. DAF system was the first generation used for the treatment in industry where the oil and grease were extracted in the tanks under flotation phenomenon. The second generation of DAF was discovered in 1960s, since then the units are used widely same way they are as used today. The typical design values for these unit plants are with surface loading rate below 5-7 m/h and flocculation time 45 min. In late 1960s a filter DAF process was introduced, where the flotation takes place above the filter. This process is called DAF/filtration (DAFF).

Moreover, at the end of the 1990s, the third generation of DAF was developed based on the idea of DAFF such as counter current DAF filtration (CoCoDAFF). In this process, recycle flow occurs above the filter media through special flow rate nozzles that are designed to disperse the bubbles widely inside the reactor (Wang et al., 2010). Rapid DAF and Aqua DAF are other recent technologies that are used with high flotation loading rate and high rate of DAF. Moreover, dissolved ozone flotation (DOF) is recently used as an alternative to DAF to decrease the cost of treatment and provide better results (Naumczyk and Marcinowski, 2012). For the past 20 years DAF has been developed widely in many designs and configurations and has led to the increase of the efficiency for industrial application (Karhu et al., 2014).

6. Pre and post treatment techniques for DAF

In order to reach a specified effluent quality, many treatment processes should be done to enhance the process. According to Liu and Nie (2016), flotation agents should be added to improve flotation, since they adhere adsorption and colloidal particles together while bubbles float. Pre-treatment of DAF for oily wastewater treatment could be done by using primary settling, coagulation or adsorption prior to flotation in order to optimize the performance of DAF. Koivunen, and Heinonen (2008) supplied DAF pilot-plant with the effluent of wastewater treatment from plant secondary or primary settling tanks. DAF performance achieved approximately 46-99 % reductions of enteric microbial numbers and 30-80 % reductions of total phosphorus, COD, and other measured water quality parameters. In addition, the efficiency of DAF process in treatment of primary effluents improved when the coagulant/ flocculant was added. Wang (2007) applied a settling tank simulation and carried out procedure involving sedimentation tank, combined with the flotation process in a small pilot study, when the influent concentration of oil was 3,000-14,000 mg/L, the effluent quality of the oil average concentration was of 300 mg/L or less, and the minimum had reached 97 mg/L, the flotation process improving the degreasing effect (Wang, 2007; Yu et al., 2017).

6.1. Coagulation/flocculation

Coagulation and flocculation are widely used in water and wastewater treatment. By adding coagulants with the help of mixing the impurities are mixed with the chemical aids and they aggregate to form stable flocs. Then by flotation the flocs can be removed by sedimentation, air flotation, or rapid filtration, Figure 2 (Jaji, 2012).

A coagulation-flocculation process is often used before the flotation tank, depending on the wastewater to be treated, in order to ensure better adhesion between the micro particles and the bubbles (Muñoz-Alegría et al., 2021).

Alshahri et al. (2021) used two coagulation modes with the combination of DAF system, such as liquid ferrate (high and low yield) and ferric chloride for the treatment of sea water. The assessment and performance of the process was conducted by measuring the removal efficiency for turbidity and other pollutants. It was concluded that the process was an efficient and cost-effective pretreatment method during algal bloom events.

Teixeira and Rosa (2006) compared coagulation/flocculation/dissolved air flotation (C/F/DAF) and coagulation/flocculation/sedimentation (C/F/S) for removing cyanobacterial cells. The result showed C/F/DAF was the best process to remove single cells of M. aeruginosa, yielding very high chlorophyll removal ranging between 93-98 %, with no toxin release to water (8-15 %), using a low recycle ratio (8 %), lower coagulant doses, and shorter flocculation time.

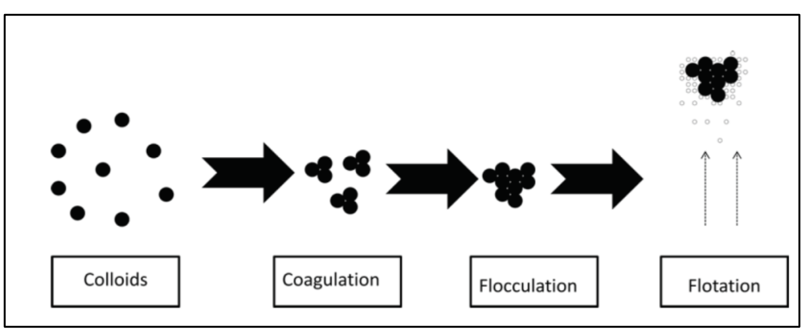

Figure 2. Coagulation/DAF system

6.2. Adsorption

Adsorption is another technique used in wastewater treatment processes. It is recognized as an efficient chemical/physical approach. The most commonly used adsorbent is activated carbon (AC), powdered AC (PAC), and granular AC (GAC) (Aziz et al., 2012). In adsorption, molecules distribute themselves between two phases, one of which is a solid, whilst the other may be a liquid or a gas. Several investigations of DAF with PAC are evaluated by Jung et al. (2016) for the treatment of several water samples, such as raw water, coagulated water, and lake water. The preliminary experiments were done by Jar test in the laboratory for the removal of turbidity and Chlorophyll-a. The results showed that at 12 mg/l PAC concentration, the removal efficiency of turbidity and Chlorophyll-a were 96.8 % and 98 %, respectively.

6.3. Treatment by chemicals

Electrochemical oxidation is the most effective treatment for various types of wastewaters, such as oil refinery, paper mill, and textile wastewater. In this process a medium that provides the ion transport mechanism between the anode and the cathode is necessary to maintain the process (Bashir et al., 2014).

Chemical treatment is an important requirement as a pre-treatment process for DAF for effective flotation. To obtain good attachment between particles and air bubbles, a relatively high surface area and destabilized flocs, as well as a hydrophobic nature, are required. The addition of the coagulant allows the oil impurities to aggregate to form larger droplet flocs (Coca et al., 2011).

Table 2 illustrates the performance of different chemicals (coagulants) which have been used for different water chemistry.

Table 2
Different coagulants usage with removal efficiencies (Saththasivam et al., 2016)

Coagulant type	Optimal dosage (ml/L)	pH	Influent (SOG mg/L)	Removal efficiency (%)
Aluminium sulphate	100	8	1,630	99.3
	50	4	500	93
	800-1,400	8	-	99 COD
	50	5	1,218	94
Ferric sulphate	120	7	1,630	99,9
	700-1,000	8	170	73
	50	5	1,218	91
Ferric chloride	500-700	8	170	73
	100	6	500	95
	50	5	1,218	92
Alumminium Chloride	50	5	1,218	93
Poly-aluminium chloride	30	6	100.9	90
Polyacrylamide	15	6	100.9	90

Treatment by chemicals is an easy and effective first treatment step to provide aggregated oil drops and larger flocs from wastewater but cost of chemicals and high volume of sludge generation are contributing problems in this treatment (Saththasivam et al., 2016).

7. Cost Study

Thompson et al. (1972) recorded costs for the three basic flotation systems which were rectangular DAF, circular (cylindrical) DAF and rectangular induced air flotation (IAF). The most economical system was the cylindrical DAF as it required less space and steel in installation and construction.

Using chemicals in the treatment process would not only improve the efficiency of the process, but would influence the running cost. El-Gohary et al. (2010) studied the comparative cost evaluation for wastewater treatment techniques, such as coagulation/precipitation (C/P) versus coagulation/DAF (C/DAF) for pre-treatment of personal care products (PCPs). The results showed initial and running costs for C/P was higher by 27.3 % and 23.7 %, respectively.

Therefore, chemical coagulation with DAF was more economical for the treatment of the wastewater. As noted by Edzwald (2011), the comparison of costs between sedimentation and DAF processes should include both capital and operation and maintenance (O&M) costs.

Floc tanks in sedimentation process required a relatively high capital cost but low operating cost. In contrast, DAF process required low initial costs but high operating cost because of its energy consumption associated with the saturator and diffusers.

8. Conclusions

After conducting the present research the following conclusions were outlined:

- The main important function of DAF is to remove suspended and colloidal solids from influent raw wastewater via flotation (rising) or by decreasing their apparent density.
- DAF technology is an efficient pre-treatment technique before biological treatment, since it removes high concentration of COD and oil and grease which can be 92.5 % and 90 %, respectively.
- Three factors: air pressure, recycle ratio and air to solid ratio affect the performance of DAF and effectiveness this process.
- Pre and post treatment of DAF lead to a better removal efficiency; however, the cost and operation of the system are high.
- The focus of future work should be on developing DAF technologies that utilize renewable energy, as well as ways to reduce the energy consumption of various elements (such as pressure pumps, motors, air compressors, and mechanical systems).

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Operativni parametri i ograničenja postupka flotacije sa rastvorenim vazduhom (DAF) za tretman otpadnih voda sa studijom troškova

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Otpadne vode
DAF tehnologija
Tretman
Zagađivači

I Z V O D

Tehnologija rastvorenog vazdušnog taloženja (DAF) je jedna od efikasnih tehnika za prečišćavanje različitih vrsta otpadnih voda koje sadrže zagađivače manje gustine od vode. Danas, zbog visokih standarda kvaliteta, otpadne vode treba tretirati visokokvalitetnim tehnikama za tretman otpadnih voda koje ispunjavaju odgovarajuće standarde. DAF može ukloniti suspendovane materijale i uljaste čestice prisutne u sirovim otpadnim vodama. Studija ima za cilj pregled sistema DAF sa njegovim operativnim parametrima i ograničenjima. Takođe, razmatra se i cena sistema. Prethodni tretmani, poput primarne sedimentacije, i naknadni tretmani poput filtracije, biološkog i hemijskog tretmana, mogu poboljšati uklanjanje zagađivača i efikasnost sistema.

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Waste Management in the Textile Industry

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ABSTRACT

In the management system of large companies, environmental protection is increasingly becoming one of the more important subsystems in terms of the generation of industrial waste. In order to manage the impact a factory's production process on the environment as efficiently as possible, it is necessary to control certain quality parameters of emissions into the environment, and activities to minimize the impact of emissions and pollution, from the moment the raw materials arrive until the product leaves the warehouse as a finished product. By analyzing the technological process, the method of waste management is defined, i.e. the types, composition and quantities of waste generated in the textile plants are determined. By constantly analyzing the existing waste management system, the currently implemented measures and possible shortcomings and omissions are constantly reviewed, on the basis of which measures to improve waste management are proposed. The paper describes the impact of waste management in the textile industry on the environment, i.e. examples of the management flow of industrially generated hazardous and non-hazardous waste - characterization of industrial waste, disposal methods and proposals for their reduction.

1. Introduction

According to the provisions of the Waste Management Law (36/2009, 88/2010, 95/2018, 35/2023), waste means any material or object that is present in the current production, service or other activity, objects that are not intended for use, as well as waste material that is present in the consumer and that is part of the production process, i.e. it is consumed for further use and must be rejected.

Therefore, waste is considered to be everything that is thrown away, intended to be thrown away or has to be thrown away.

In accordance with Waste Management Law (36/2009, 88/2010, 95/2018, 35/2023), waste is divided, according to the source, into:

1) communal waste (household waste);
2) commercial waste; and
3) industrial waste.

Waste can be classified according to its composition (waste oils, waste tires, used accumulators and batteries, etc.) or depending on the dangerous characteristics that affect human health and the environment (inert, non-hazardous, and hazardous waste). Some classification systems combine different ways of classifying waste within one system. Industrially generated non-hazardous waste predominates.

Every movement of waste is accompanied by a document on the movement of waste, and its form is prescribed by a special Rulebook (17/2017), and

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consists of four parts:

Part A - data on waste;
Part B – data on the waste producer;
Part C – data on the waste carrier; and
Part D - data on the recipient of the waste.

Each member of this chain is obliged to guarantee the accuracy of the data by signing and certifying their part and, at the end of the year, the summary report is sent to the Environmental Protection Agency on the specially designed portal of that state institution. Textile wastes arise out of many production processes, such as fiber and filament manufacture, spinning, weaving, knitting, nonwoven, and clothing manufacturing (Bhatia et al., 2014). In this context, textile wastes can be classified as pre-consumer and post-consumer wastes (Chen and Burns, 2006; Damayanti et al., 2021). Pre-consumer textile waste includes manufacturing waste from the processing of fibers, yarn, fabric, and nonwovens and clothing manufacturing (Rani and Jamal, 2018). Pre-consumer textile waste is generally seen as “clean waste” as it is released during the textile production process (Chavan, 2014; Labayen et al., 2022). About a quarter of chemicals produced globally are used in the textile industry (Greenpeace International - Dirty Laundry, 2011). Numerous chemicals are used for textile production, mainly in the wet processing and many of them (nearly 2000 different chemicals), have adverse impacts on health.

Some chemicals evaporate, while others are dissolved in treatment water which ultimately goes back to the environment, and some chemicals remain in the product (Choudhury, 2014).

Producing cellulose-based fibers also necessitates large amounts of chemicals and some of the chemicals used are sources of concern. Producing the fibers requires using chemicals too, for example for dyes or finishing treatments. This part of the production is estimated to use approximately 43 million tons of chemicals globally (Ellen MacArthur Foundation, 2017).

The waste generated by producing and consuming textiles is major problem. Textile consumption around the world is calculated to be over 100 million tons (Harder, 2019). However, the rate of recycling is rather low: barely 13 % of the total material input is in some way recycled after usage. Of this recycled 13 %, a minuscule part is used to produce new clothing-less than 1 % (Abede, 2021).

The rest is recycled into other, lower-value items such as insulation material, wiping cloths or mattress stuffing (Ellen MacArthur Foundation, 2017). Textile and clothing waste causes environmental problems and deterioration of ecological balance. Unfitting and uncontrolled disposal of waste cause major problems, (Xie et al., 2021).

Recycling of textile waste and diversifying the content of recycled raw materials could be a way to support the country’s economy. The employment opportunities in the textile sector and in other sectors increase with well-run waste management. The recycling sector is an important supplier to many industries, and wastes are considered to be cheap raw materials (Gizem et al., 2023).

1.1. Treatment of textile industry plants generated waste

In accordance with the Rulebook (56/2010, 93/2019, 39/2021), Table 1 shows an example of waste generated list by the performance of certain business activities of the textile factory work units.

Table 1
Example of a list of waste generated from the textile industry (Alendarević, 2022; Krivokuća, 2022)

Name of the waste	Note
Textile industry waste	
Paints and pigments containing hazardous substances	Residues after painting that go into the waste water pool
Sludge from wastewater treatment at source	It is possible that sludge will remain after the treatment of waste water, after the reconstruction of the system
Waste from processed textile fibers	Whole pieces (white and colored), pieces that are created by cutting off a certain part during the formation of the final product Specific pieces - "laces" (potential official by-product)
Waste not otherwise specified	Other textile waste - whole pieces, cutting residues, textile fibers, etc.
Wastes from production, formulation, supply and use and removal of paints and varnishes	
Waste paint and varnish	Waste soluble powder dyes for the textile industry
Waste hidraulic oils	
Other hidraulic oils	From cooling compressors, from compressors for compressing air
Waste motor oils, gear oils and lubricants	
Other waste motor oils, gear oils and lubricants	They do not remain after servicing the vehicle, because the service technician keeps them

Table 1 continued
Example of a list of waste generated from the textile industry (Alendarević, 2022; Krivokuća, 2022)

Name of the waste	Note
Packaging (including specially collected packaging in municipal waste)	
Paper and cardboard packaging	Cardboard boxes, partitions, Cardboard packaging („hilzne“)
Plastic packaging	A. Used polyethylene bags and stretch film, B. stands for packaging („hilzne“) made of various materials (polypropylene, polystyrene, colored PET), C. plastic packaging („hilzne“, mainly made of polypropylene) D. plastic packaging, barrels of auxiliary substances used in the process of dyeing product, they are made of HDPE – one of the types of polyethylene; F. PE bags for transport various type of products
Wooden packaging	Broken pallets that are not of EU standards
Metals (including their alloys)	
Aluminium	Waste from scrapped machines, boiler house overhaul, etc.
Iron and steel	Waste from scrapped machines, boiler house overhaul, etc.

Due to its specificities, the complete treatment of waste in manufacturing textile plants is defined on the basis of signed contracts only with companies that are authorized and registered for the circulation and processing of waste which have all the necessary documentation on the fulfillment of the conditions in terms of environmental protection. All necessary conditions for its management are prescribed for each type of waste. Also, the method of disposal of waste, i.e., its final disposition, is recorded and operational instructions are drawn up (within job descriptions, work methods, etc.) by workplace or for a group of jobs. These operating instructions represent binding activities for all employees in textile manufacturing plants.

The locations of collecting places, labeling and sorting waste materials in manufacturing textile plants are defined according to the place of their origin within the organizational unit. Places of temporary storage can be located outside the production or warehouse areas (concrete plateau) within the factory area. Any generated waste is disposed of, i.e. handed over to operators who have the appropriate permit. Each type of generated waste is assigned a waste index number through characterization in an accredited laboratory. The basic principles of the waste management hierarchy are shown in Figure 1.

The resulting waste is handed over to the authorized operator with the document on the movement of waste, who closes the document on the movement of waste within the legal term, i.e. submits information on the recipient of waste (storage, exporter, recycler, and co-incinerator).

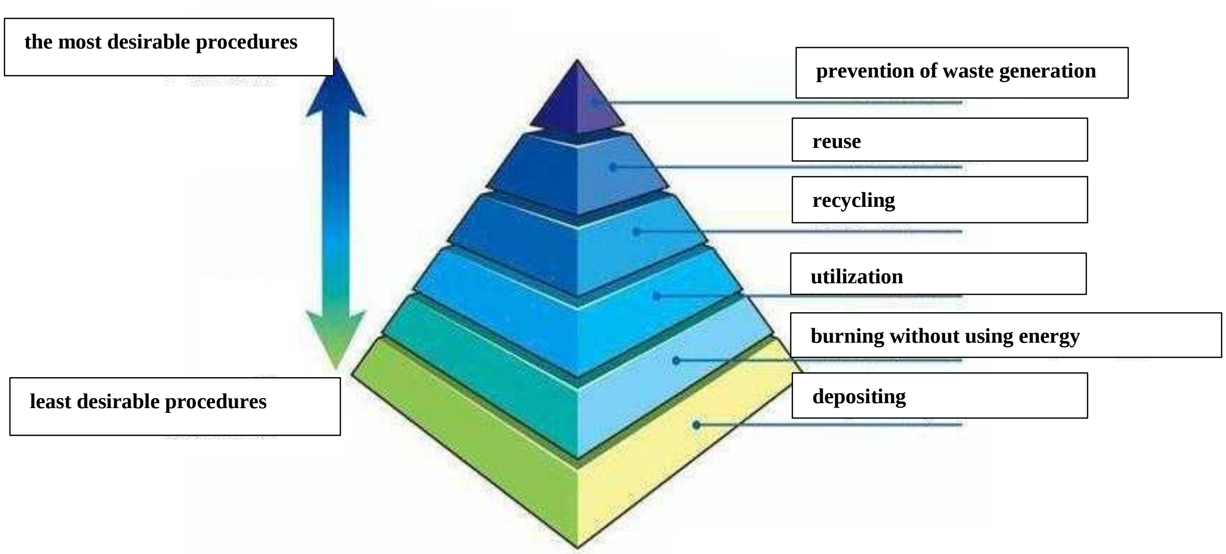


Figure 1. Hierarchy of waste management (Metaling p.u.t. https://www.metaling.rs/karakteristike-odrzivog-upravljanja-otpadom.html)

2. Material and Methods

2.1. Method of storage, treatment and disposal of waste

The production process in textile plants results in the generation of certain types of waste materials, which are deposited in sacks, boxes, wooden boxes, or containers designated for that purpose, placed within the work unit framework whose activities generate the type of waste according to the type of technological/production process. Although there are several methods for disposing of clothing waste, the most effective methods are recycling and reuse. The assessment of waste clothing is very complex because clothing is made from different raw materials and may contain different additives (Risteski et al., 2020). Garments can have many components such as labels, sewing thread, buttons, zippers, and interlining, and these components make the separation process difficult. Clothing recycling and textile recycling are two independent topics that are needed to be considered separately (Xie et al., 2021).

Places for the disposal of certain waste are marked with signs on which there are inscriptions about the name of the waste. Figure 2 shows an example of marking the storage area in a textile manufacturing plant. Signs for waste marking are placed at locations intended for proper and orderly storage of waste within the company.

Figure 2. Marking of waste collection locations (Alendarević, 2022; Krivokuća, 2022)

3. Results and Discussions

Packaging is an important element of the industry providing protection, handling, marketing promotion, and other functions. The common packaging materials used in the industry are plastics and paper-based.

However, textile packaging contributes a significant amount of solid waste that damages the environment. The industry has responded in different ways to reduce the waste generation by promoting recycling, reuse, energy recovery, minimization, and using novel compostable polymers. This management of packaging waste is being adopted by large retailers and brands in their effort to promote sustainability (Doice, 2021). Solid waste dumping is a crucial risk, especially for developing countries. Insufficient collection and thoughtless disposal of solid waste causes land and air pollution and creates risks to human health and the environment. Thus, the management of textile waste has gained importance, and developing nations should spend a major part of their municipal revenues on waste management.

3.1. Packaging waste management flow: recyclable plastic, cardboard and wooden pallets

Recyclable plastic mostly comes from tertiary packaging, i.e. stretch film that wraps the pallet with goods during transport, plastic packaging (sleeves) on which the yarn arrives, from the stand and bumper on which the sleeves arrive together with the yarn, from discarded PE bags used to transport textile products in various stages of production, as well as empty packaging from products that are not considered hazardous materials. Recyclable cardboard/paper comes from cardboard boxes, i.e. secondary packaging in which many products of raw materials are packed. This also includes the paper wrapper in which the packaging for packaging textile products arrives and cardboard sleeves that serve as yarn carriers.

Packaging waste is collected separately at the point of generation, separately by type of material and handed over to an authorized operator for the collection and transport of packaging waste. Disposal of cardboard waste, pallets, metal waste, and plastic is shown in Figures 3 (a-c).

a)

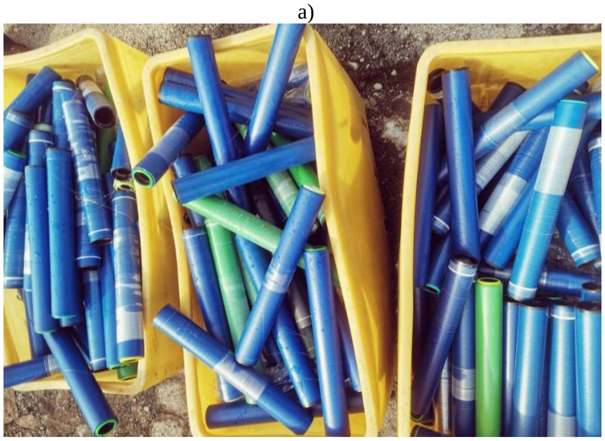
b)

c)

Figure 3. (a-c) Disposal of old paper and cardboard waste (Alendarević, 2022; Krivokuća, 2022)

All plastic and metal sleeves (yarn carriers) on which the polyamide fiber is delivered are returned to the supplier - as returnable packaging, which reduces the amount of generated industrial waste, Figure 4a and 4b.

a)



b)

Figure 4. Plastic and metal sleeves - reuse (Alendarević, 2022; Krivokuća, 2022)

Cardboard sleeves on which polyamide fibers are wound have represented a problem for disposal for a long time. Although they have the character of non-hazardous waste, they are difficult to cut, soften and shred, i.e. they are prepared for recycling due to their high hardness and glue in them, Figure 5a and 5b.

a)

b)

Figure 5. Storage of non- returnable cardboard boxes - a) before and b) after reorganization (Alendarević, 2022; Krivokuća, 2022)

After handing over to an authorized local non-hazardous waste collector/storer, with whom a contract must be signed, the cardboard boxes are shredded by mechanical treatment (Figure 6), ground and baled in a waste warehouse with valid permits for mechanical treatment, and then handed over to a larger legal entity that collects them along with waste cardboard for recycling (Packaging Law 36/2009, 95/2018).

Figure 6. Shredded cardboard boxes, ready for baling (Alendarević, 2022; Krivokuća, 2022)

Hard plastic packaging, HDPE barrels of auxiliaries for dyeing textile products, which are used in the production process, are rinsed with water immediately after emptying in the process of preparing the dyeing solution. Washed packaging has the character of non-hazardous waste. All plastic waste is temporarily stored on pallets on a concrete platform within the factory circle, marked and fenced, Figures 7-11.

a) b)

Figure 7. Hard recyclable plastic disposal site (Alendarević, 2022; Krivokuća, 2022)

a) b)

Figure 8. Formed mini eco – island: a) for the disposal of recyclable paper/cardboard sleeves and b) soft plastic (foil) within the factory (Alendarević, 2022; Krivokuća, 2022)

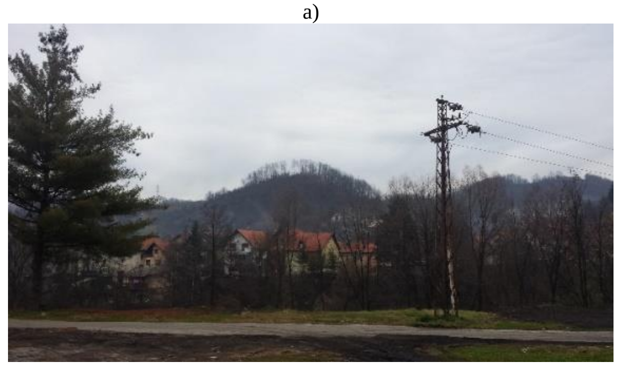
a)

b)

Figure 9. Collection of waste cardboard and cardboard sleeves (Alendarević, 2022; Krivokuća, 2022)

Wooden packaging waste pallets are used to transport products. As long as they are usable, they are used for repacking goods in the warehouse area. When they break, they become packaging wood waste.

a)



b)

Figure 10. Wood waste storage a) before and b) after reorganization (Krivokuća, 2022; Alendarević, 2022)

Figure 11. Wooden packaging – pallets that are returned tothe supplier (Krivokuća, 2022, Alendarević, 2022)

In order to reduce the amount of waste generated, the following measures are taken:

• plastic and metal sleeves (yarn carriers) are returned to the yarn manufacturer as returnable packaging - reuse, Figure 11.;

• wooden pallets that are returned to the yarn producer - reuse;

• part of the hard plastic used to stabilize the polyamide yarn during transport is returned to the supplier - reuse;

• part of the hard plastic (HDPE barrels) from auxiliaries for textile dyeing are returned to the supplier - reuse;

• waste generated after the servicing of a device, machine or vehicle by contract remains with the servicer and the servicer has the obligation to dispose of that type of waste;

• slag (potential by-product) that remains after thermal combustion of coal can be used as an alternative building material for construction work within the factory, for the construction of embankments, and local roads to waste water treatment system - potential registered by-product;

• specific textile remnants - "laces" (potential by-product) produced in the finishing work unit are used for horticultural purposes for tying young shoots of raspberry fruit - a potential registered by-product, Figure12. (Alendarević, 2022; Krivokuća, 2022)

3.2. Non-hazardous textile waste management flow

Undyed textile waste originates from the working unit of knitting - whole scrap products, threads (fibers) of yarn left behind during knitting in machines and on spools (sleeves) - knitting phase; and whole scrap products, parts of products that fall off during cutting and sewing - finishing stage (assembly). One part that is discarded during the finishing work is the textile remains, the so-called "noodles" - it has a further use value, for example, in agriculture, for tying young fruit shoots, Figure 12.

a) „bater“ and „štrips“

b) „pucval“

c) SULZER edges

Figure 12. Examples of waste from textile fibres processed (Alendarević, 2022; Krivokuća, 2022

Colored textile waste is whole scrap products from the working units of dyers and in packages, without yarn and offcuts.One of the solutions for the disposal and textile waste treatment is the takeover by an authorized operator, which has permits for transport, storage, treatment and export for the treatment of textile waste. According to the results of the analysis, the subject waste is satisfactory in terms of use for thermal treatment and can be used for the same according to the Rulebook) 56/2010, 93/2019, 39/2021), Figure 13.

Particular attention should be paid to the recycling of polyamide, because the fibers are mixed and contain polyamide and lycra in the ratio 85-94 % : 6-15 %. Lycra is cross-linked into the polyamide structure and cannot be technically separated from the polyamide, which creates problems in the later stages of recycling.

a)

b)

c)

Figure 13. Textil waste disposal location a) before and b,c) after reorganization (Alendarević, 2022; Krivokuća, 2022)

The Waste Management Law (36/2009, 88/2010, 95/2018 - other laws, 35/2023) mandates that the hierarchy of waste management be respected and that waste be recycled if possible. If there are no recyclers, one of the solutions is to give the waste to be used by cement plants, which have a permit for co-incineration of this type of waste. Although the situation with companies that have a permit for the transport and storage and/or treatment of waste is very specific, because there are only a few companies that operate and receive textile cotton and polyamide waste, the policy of each company should be to dispose of waste in a legal way, with the respect to hierarchy, so treatment always precedes burning in that order of priority.

4. Conclusions

In the production facilities of the textile industry waste should be handled in a way that ensures the reduction of the harmful impact of waste and the protection of the environment. In every production textile plant, there is an organized collection and temporary storage of waste, for further treatment, where it has a useful value, as well as efficient removal and handing over to the authorized operators for waste management.

Special attention should be paid to strengthening the existing and developing new measures for the establishment of an efficient waste management system based on a well-written waste management plan, which would provide and elaborate all mechanisms for the most rational and sustainable waste management, with clear management plans for special waste flows (hazardous waste, packaging, non-hazardous, communal), with consistent respect for the hierarchy of waste management. Reduction of waste at the source, reuse, recycling of waste, all as a solution before final disposal.

In order to reduce the harmful impact of the textile industry on the environment, it is necessary to work on the development of the awareness of textile producers and users themselves, to give priority to the use of materials that have the possibility of recycling compared to synthetic materials, to reduce the use of chemicals during the processing and dyeing of fabric, and to switch to the production of clothes that would have a longer shelf life.

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Upravljanje otpadom u tekstilnoj industriji

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Industrijski otpad
Opasan otpad
Neopasan otpad

I Z V O D

U sistemu upravljanja velikim privrednim subjektima, zaštita životne sredine, sa aspekta stvaranja industrijskog otpada, sve je više jedan od njegovih važnijih podsistema. Da bi se što efikasnije upravljalo uticajem proizvodnog procesa jedne fabrike na životnu sredinu, neophodno je kontrolisati određene parametre kvaliteta emisija u životnu sredinu, kao i aktivnosti na minimiziranju efekata emisija i zagađenja, od momenta prijema sirovina do trenutka kada proizvod napušta skladište gotovog proizvoda. Analizom tehnološkog procesa definiše se način upravljanja otpadom, odnosno definišu se vrste, sastav i količine otpada koji nastaje u tekstilnim pogonima. Kroz stalnu analizu postojećeg sistema upravljanja otpadom, sagledavaju se mere koje se trenutno sprovode, kao i eventualni nedostaci i propusti, na osnovu kojih se predlažu mere za unapređenje upravljanja otpadom. U radu je opisan uticaj upravljanja otpadom u tekstilnoj industriji na životnu sredinu, odnosno primeri toka upravljanja industrijski nastalim opasnim i neopasnim otpadom - karakterizacija industrijskog otpada, načini odlaganja i predlozi za njegovo smanjenje.

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Evaluation of Basalt Cutting Waste in Coloring of Different Ceramic Glaze Compositions

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ABSTRACT

Color effects in ceramic glazes play a decisive role in the aesthetic and attractiveness of ceramic pieces. The colorants used in glazes interact with the ceramic materials during the firing process, resulting in a wide range of fascinating colors and effects. Due to the natural properties of basalt such as high compressive strength and wear resistance, this natural volcanic rock is attracting a lot of attention when used in ceramic production processes. The aim of this study is to evaluate the effects of basalt cutting waste (BCW) obtained from a stone company in Kayseri, Turkey, on the color effect of ceramic glazes in combination with different frits. For this purpose, glazes were prepared in which BCW was incorporated in different weight percentages of 0-20 % together with different frits. The glazes were characterized by analyzing chemical, phase, and thermal behavior of BCW using X-ray fluorescence (XRF), X-ray diffraction (XRD), and thermal microscopy, respectively. The prepared glazes were then applied to engobed wall tiles and fired at a temperature of 1,200 °C in a laboratory furnace. After firing, the glazed surfaces were subjected to color analysis, while the phase composition was analyzed by XRD. The microstructure analysis was carried out using electron microscopy (SEM/EDS). Increasing the proportion of BCW in the glaze compositions resulted in a change of the color of the finished surfaces from cream to yellow-beige tones. This study sheds light on the potential use of BCW as a coloring agent in the production of ceramic glazes.

1. Introduction

Industrial advances have the potential to improve people's health and living conditions. However, it is important to recognize that industrial development can also have negative consequences such as pollution and resource scarcity. The ceramics production sector, which plays a crucial role in the daily living environment, often generates significant amounts of waste without an effective recovery process. As technology advances in the manufacture of ceramic products, the demand for raw materials increase. However, the sourcing of such materials can lead to air and environmental pollution, depending on the energy sources used. In recent years, various factors, including conflicts and the ongoing pandemic, have led to challenges in raw material supply, subsequently impacting prices in the economy. These circumstances have highlighted the importance of sustainable practices and the development of efficient processes that minimize waste generation and reduce pollution in the ceramics industry.

The universal problems experienced in recent years

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are limiting the raw material resources and thus increasing cost. Improving the sintering process or replacing the initial raw materials with waste materials are used as two different methods of reducing production costs. For this purpose, studies on the use of waste materials have been increasingly carried out in recent years. To this purpose, cullet (Garbonchi et al., 1999; Matteucci et al., 2002; Gennaro et al., 2003), various industrial wastes (Andreola et al., 2002; Karamanov et al., 2006), and also some outcrops with an acidic component such as volcanic ash and zeolite (Abadir et al., 2002; Dana et al., 2004; Torres et al., 2004) are used. These materials find restricted application at various stages within the traditional ceramic industry.

Basalt is a preferred choice for various applications because of its durability and resistance to stains. Nevertheless, when shaping and cutting this natural stone product, a substantial amount of dust and crumbs can be generated as waste. The waste powders of basalt are stored by business owners in an area that is not operational (Koçyiğit and Çay, 2019).

Basalt, which has a fine-grained structure in different colors from grey to black, is in the group of volcanic rocks. It occupies a very large area (2.5 million square meters) on the earth surface and is a cheap and easily available raw material (Ercenk et al., 2018).

The chemical composition of basalt is SiO_2 and Al_2O_3 as major oxides with about 40-55 % and 10-20 % SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO and there are other oxides such as K_2O and TiO_2 (Ercenk et al., 2018).

The widespread use of this material in glass-ceramic production is due to the high proportion of silica in its chemical composition. Basalt-based glass-ceramics have good resistance to wear, abrasion, and chemicals. In addition, this material is also known for its good heat, sound, and fire resistance (Ergul et al., 2009; Binici, 2007; Ercenk et al., 2018).

The glaze applied to the surface of ceramic materials plays an important role in gaining the necessary properties (such as hygiene, visual effect, and strength) in the use of the product. Coloring of glazes, features such as glossy/matt, and surface smoothness are provided by the harmony of the colorants and additives used together with the glaze raw materials.

In recent years, the use of waste materials in the development of glazes has attracted considerable attention, both in terms of reducing running cost and environmental impact. When the studies in the literature in this area are examined, it can be seen that the waste materials are used in different areas as a source of pigment, glaze, and additive to the body. In the field of glaze application, there are studies in the literature on the use of marble waste (Yesilay et al., 2017), borax solid waste (Karasu et al., 2011), vitrified waste (Tarhan et al., 2017), fly ash (Bayer Öztürk, 2010), and zinc ore waste (Bayer Öztürk et al., 2017).

The previous studies demonstrate the potential of basalt-based glazes for ceramics, offering benefits such as lower firing temperatures, cost-effectiveness, stability, and attractive color options. Notably, the basalt from different locations shows promise in producing high-quality, pressure-resistant, and economically efficient glazes (Yilmaz et al., 2006; Andric et al., 2012).

The aim of this study was to investigate the potential of using basalt-cutting waste powder in ceramic tiles to improve the properties of the glaze, including color, surface properties, and sintering behavior. To achieve this, the waste powder obtained from BCW was incorporated into three different glaze compositions. The study focused on investigating the sintering behavior and physical properties of the final ceramic product resulting from these glaze formulations. By investigating these aspects, the effectiveness of using basalt-cutting waste powder in improving the glaze quality of ceramic tiles was to be evaluated.

2. Experimental Procedure

The chemical analysis of BCW, which was supplied from Emre Taş Mining (Kayseri, Turkey), was given in Table 1. The chemical analysis was conducted with XRF (Rigaku ZSX Primus model). The X-ray analysis (XRD, Rigaku Miniflex 600) of the BCW showed that Andesine ($Al_{0.735}$ $Ca_{0.24}$ $Na_{0.26}$ O_4 $Si_{1.265}$), Anorthite ($Al_2Ca(SiO_4)_2$), and Quartz (SiO_2) are main phases in its composition (Fig.1). The termogravimetric/differential thermal analysis (TGA/DTA- STA 409PG LUXX) were carried out to investigate the thermal behavior of BCW.

Additionally, thermal behavior of frits was examined using the thermal analysis microscopy (MISURA). The opaque and matt frits used in experimental researches were supplied from Gizem Firit Company and their chemical compositions ranges are given in Table 3. The BCW percentage in the glaze compositions was varied between 0-20 wt. %, while the percentage of dry frit (92 wt. %), kaolin (8 wt. %), sodium tripolyphosphate (STPP 0.2 g) was kept constant.

The wet milling system was used to prepare the frits with addition of 60 cc of water (residue <2 % at 63 µm). The glazes at 1,500 g/L were applied on 5×5×0.7 mm engobed tiles and fired in a laboratory kiln (at 1,200 °C for 6 h). The codes of glazes are presented in Table 2. Phase analysis of opaque and matt glazes prepared with BCW (0-20 % waste addition) was performed with an X-ray diffraction.

The color parameters (L*, a*, b* values) were determined using a Minolta CM-3600d color measuring device in the color analysis of glazed samples. The development of the phases in the microstructure was determined by examining the glazed samples containing 20 wt. % basalt-cutting waste by scanning electron microscope (SEM, Zeiss EVO 50 EP, an accelerating voltage of 20 kV to ensure accurate elemental composition and microstructure determination).

Table 1
Chemical composition (wt. %) of basalt cutting waste (BCW)

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	TiO_2	K_2O	MnO	P_2O_5	SO_3	Loss of ignition (LOI)
49.47	17.24	10.26	10.35	6.24	3.42	1.33	0.61	0.16	0.22	0.07	0.53

Table 2
Glaze mixture proportions and their codes

Glaze code	Frits (Opaque (O)-Matt (M)-Transparent (T)) (wt. %)	Kaolin (wt. %)	Basalt cutting waste (wt. %)
M0	92 M	8	0
M5	92 M	8	5
M10	92 M	8	10
M15	92 M	8	15
M20	92 M	8	20
O0	92 O	8	0
O5	92 O	8	5
O10	92 O	8	10
O15	92 O	8	15
O20	92 O	8	20
T0	92 T	8	0
T5	92 T	8	5
T10	92 T	8	10
T15	92 T	8	15
T20	92 T	8	20

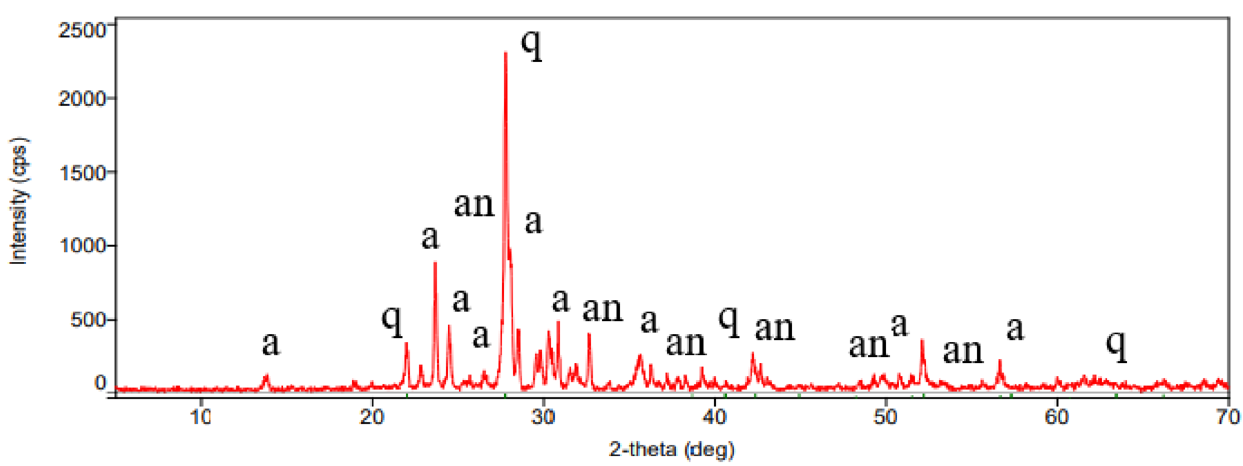


Figure 1. Phase analyse pattern of BCW
(**a**: Andesine, $Al_{0.735}Ca_{0.24}Na_{0.26}O_4Si_{1.265}$, **an**: Anorthite, $Al_2Ca(SiO_4)_2$, **q**: Quartz SiO_2)

3. Results and Discussions

3.1. Characterization of basalt cutting waste

The DTA/DTG analysis results of BCW are given in Figure 2. The mass loss is indicated by four exothermic peaks which are 0.097 µV/mg mass loss at 670.9 °C, 0.247 µV/mg mass loss at 953 °C, 0.311 µV/mg mass loss at 1,036 °C, and 0.413 µV/mg mass loss at 1,188 °C, respectively. The phase analysis of the BCW (Figure 1) revealed the presence of large amount of feldspar (anorthite and andesine) and quartz. In the available literature, it is suggested that the presence of albite and pyroxene phases may be responsible for the observed endothermic peaks (Mahmood, 2014). Additionally, no crystallization peak was detected in the DTA analysis of the BCW. The melting behavior of the BCW was analyzed by a heat microscopy between 1,166 and 1,214 °C and the results are given in Figure 3. As can be seen in the analysis, the temperature at which it is subjected to a 5 % change in size gives the sintering temperature if the sample image is as assumed to be 100 %.

The softening point of the sample is examined at 1,188 ºC, at which the liquid phase appears on the surface of the sample. The spherical shape was observed at 1,198 ºC. In this step, the sample consists entirely of the liquid phase, and the shape of the sample is controlled by the surface tension.

After that sample reached the shape of hemisphere at 1,206 ºC and the height of the sample decreased by half the width at this temperature. The last step is called the melting point at which the sample fell below a third of its original height (Paganelli and Sighinolfi, 2008; Bayer Öztürk et al., 2020).

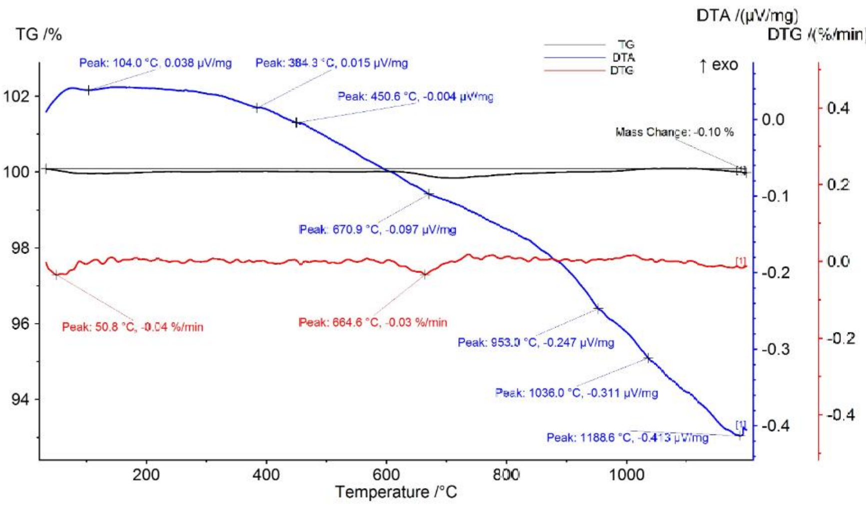


Figure 2. The thermal behavior characterisation result of BCW (DTA-DTG graph)

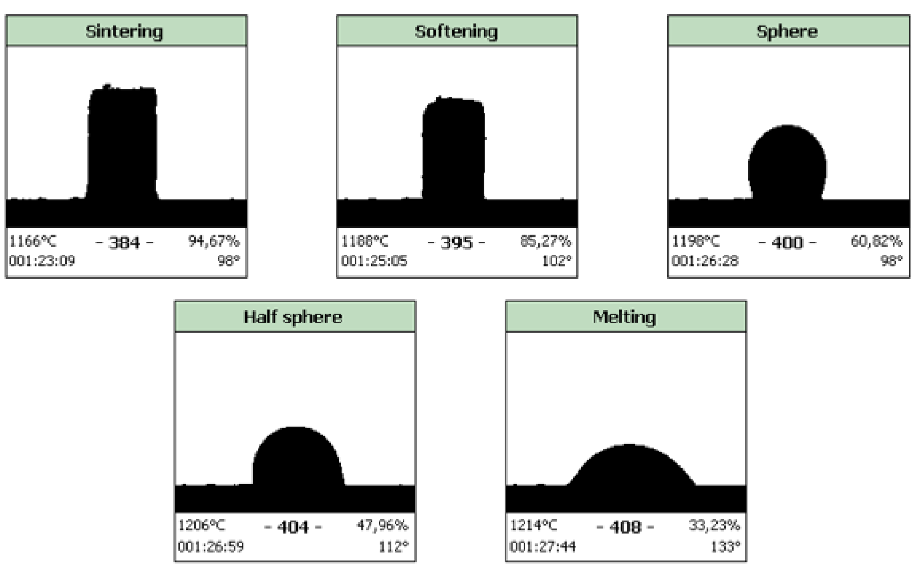


Figure 3. Heat microscopy results of basalt cutting waste

3.2. Characterization of the obtained glazes

The chemical compositions of studied frits supplied from Gizem Frit are presented in Table 3. As it is seen in chemical analysis, the percentage of SiO_2, B_2O_3, K_2O oxides is higher in opaque and transparent frits than in the matt frit. It is also noteworthy that the opaque frit has a high ZrO_2 content compared to the matte and transparent frit.

The characteristic temperatures were determined between 740 and 1,102 °C for matt frit, 840 and 1,264 °C for opaque frit, 816 and 1,208 °C for transparent frit in Table 4. The color of obtained glazes based on BCW were changed from a light yellow to beige color and the firing colors of glazed tiles fired at 1,200 °C can be seen in Figure 4. The increasing amount of BCW (from 5 to 20 wt. %) in the glaze composition led to a change from beige to yellow shades. The color parameters (L*-a*-b* values) of the glazed tiles are shown in Table 5.

Compared to other glaze samples, low L-values were achieved for matte (L* 58.19) and opaque (L* 61.73) glaze applications with 20 wt. % BCW. As the proportion of BCW in the glaze composition was increased, it was observed that the a* and b* values also increased. In this point, the effective parameter to change the color of glazes is the amount of iron oxide (10.26 wt. %) derived from BCW.

For the transparent glaze with 20 % BCW, the L* value was 49.11, the values for a* and b* were 2.76 and 33.71 respectively.

Table 3
The chemical compositions of matt, opaque and transparent frits

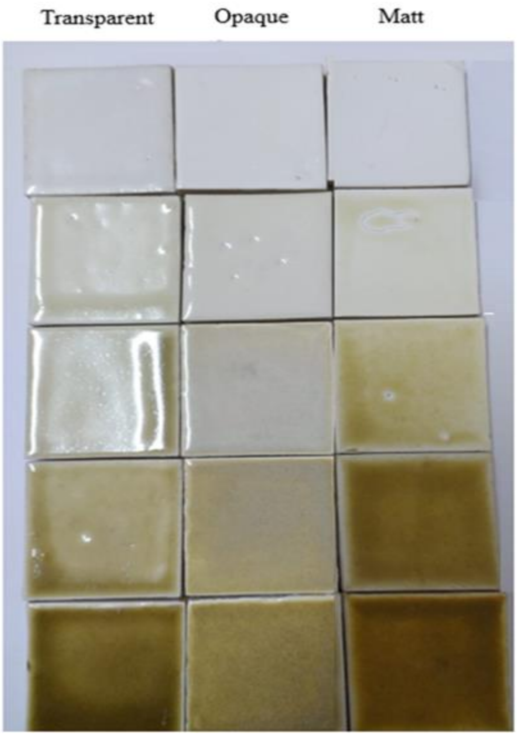
Frit	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**Na_2O**	**K_2O**	**ZnO**	**B_2O_3**	**TiO_2**	**ZrO_2**
Matt	47-49	13-15	0.05-0.1	12-14	0.25-1	6-8	0.05-0.5	17-19	0.5-2	0.05	-
Opaque	54-57	5-7	0.05-0.1	8-10	2-4	1-3	3-5	5-7	9-11	0.05	6-8
Transparent	54-57	8-10	0.05-0.1	12-14	0-1	1-2	5-7	4-6	9-11	0.05	-

Table 4
Typical points result of frits obtained by hot-stage microscopy (°C)

Sample	**$T_{sintering}$ (ºC)**	**$T_{softening}$ (ºC)**	**T_{sphere} (ºC)**	**$T_{hemisphere}$ (ºC)**	**$T_{melting}$ (ºC)**
Matt (MT)	740	1,082	-	1,092	1,102
Opaque (OP)	840	1,012	1,076	1,202	1,264
Transparent (TR)	816	962	1,014	1,108	1,208

Table 5
The color parameters of glazed tiles

Sample	**L***	**a***	**b***
M0	89.73	-0.29	2.82
M5	88.37	-1.62	10.25
M10	80.65	-1.15	22.91
M15	64.20	3.47	34.62
M20	58.19	7.96	36.78
O0	90.17	-0.52	1.69
O5	85.17	-1.22	8.74
O10	76.48	-0.16	12.44
O15	68.43	1.35	16.88
O20	61.73	3.01	25.67
T0	86.86	-0.35	1.30
T5	81.65	-1.75	13.41
T10	67.82	-0.25	23.48
T15	68.93	0.11	27.14
T20	49.11	2.76	33.21



Addition of BCW (wt. %)

Standard glazes
(0 wt. % BCW)

5 wt. % BCW

10 wt. % BCW

15 wt. % BCW

20 wt. % BCW

Figure 4. The effect of BCW addition on glaze applications

The higher color change was observed when the basalt-cutting waste was added at a proportion of 20 wt. %.

XRD and SEM analyses were conducted on both standard samples (without basalt-cutting waste) and glazed samples containing 20 wt. % BCW. The results are depicted in Figures 5-7, illustrating the phases present in the glazed samples. In the case of opaque glazes (from O0 to O20), the major crystalline phases identified were quartz, zircon, and anorthite. Meanwhile, for matt glazes (from M0 to M20), the phases observed included quartz, anorthite, diopside, and aluminum silicate.

These analyses provided insight into the crystalline structures and composition of the glazes, offering a better understanding of the materials' behavior and the impact of incorporating basalt-cutting waste on the phase composition of the glazed samples. No crystalline phases were observed in transparent glazes (from T0 to T20). In XRD analysis, it was determined that the addition of BCW to the glazes resulted in an increase in the intensities of the anorthite and diopside phases.

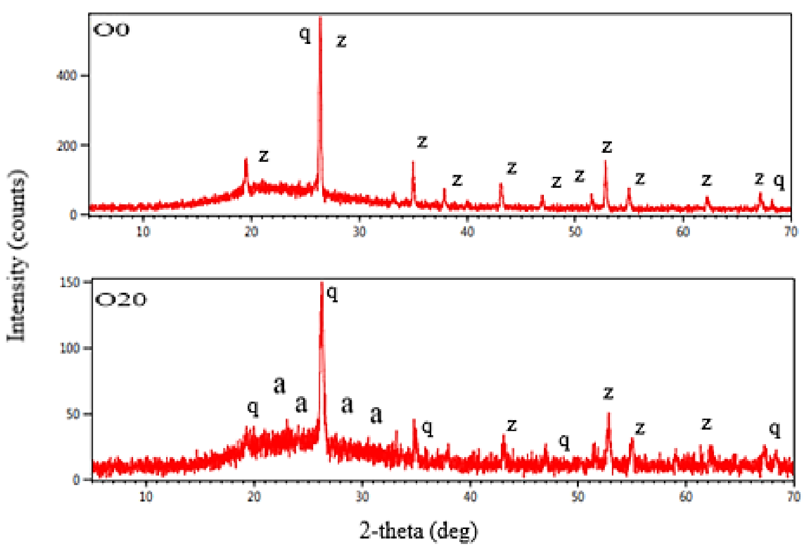


Figure 5. XRD patterns of O0 (standard) and O20 glazes (**q**:quartz, **z**:zircon, **a**:anorthite)

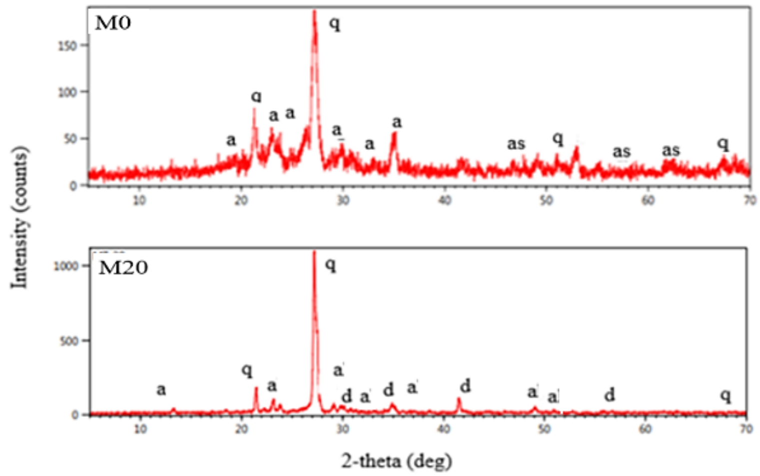


Figure 6. XRD pattern of M0 (standard) and M20 glazes (**q:**quartz, **as:** aluminum silicate, **a**:anorthite, **d:**diopside)

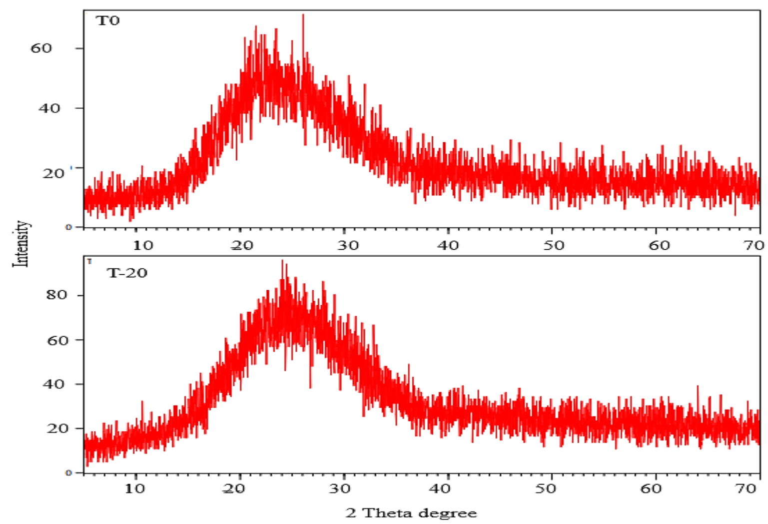


Figure 7. XRD pattern of T0 (standard) and T20 glazes (amorphous phase)

According to the SEM-EDS results of the opaque glazed tiles, while zircon crystal was present at 60.92 wt. % Zr, 20.49 wt. % Si, 18.59 wt. % O in standard opaque glazed tiles, other zircon region for O20 sample contained 22.46 wt. % O, 33.66 wt. %Si, 4.85 wt. % Al, 23.88 wt. % Zr, 3.30 wt. % Zn, 5.01 wt. % Ca, 2.25 wt. % Fe, 1.26 wt. % Mg, 1.18 wt. % Na as can be seen in Figure 8. It shows that the zircon contained in the opaque frit was detected in the phase and microstructure analyses of the opaque glazed samples.

Anorthite containing phase region involved 47.78 wt. % O, 30.46 wt. % Si, 4.03 wt. % Na, 10.33 wt. % Al, 4.67 wt. % Ca, 0.98 wt. % K, and 1.74 wt. % Zn for standard matt glazed tile in Fig. 10. On the other hand, anorthite region was detected as 42.26 wt. % O, 25.51 wt. % Si, 6.11 wt. % Al, 6.94 wt. % Ca, 2.37 wt. % K, 2.80 wt. % Na, 11.38 wt. % Zn and 2.63 wt. % Fe in M20 (Figure 9).

It was determined that the addition of BCW formed a needle-like anorthite crystal, especially in the matt-glazed sample. It has been reported in the literature that anorthite crystallizes in the glazing as a needle-like shape (Tunali and Selli, 2014; Tunali et al., 2015). As detected in the EDS analysis, samples containing basalt-cutting waste in the glassy phase contain iron. This proves that there are iron oxide crystals in the glassy phase, although they cannot be detected in XRD, and color development occurs depending on iron oxide (Gultekin, 2020).

According to the SEM-EDS results of the transparent glazed tiles, the amorphous phase region contained 32.69 wt. % Si, 46.58 wt. % O, 6.98 wt. % Ca, 4.88 wt. % Al, 4.26 wt. % Zn, 3.01 wt. % K, 1.60 wt. % Na for standard transparent glaze. Additionally, other amorphous phase region contained 32.21 wt. % Si, 47.25 wt. % O, 5.14 wt. % Ca, 7.03 wt. % Al, 1.78 wt. % Zn, 2.31 wt. % K, 1.86 wt. % Na and 2.44 wt. % Fe for T20 as can be observed in Figure 10. The presence of iron content was more prominent due to the basalt waste in the glassy phase than in the standard transparent glaze.

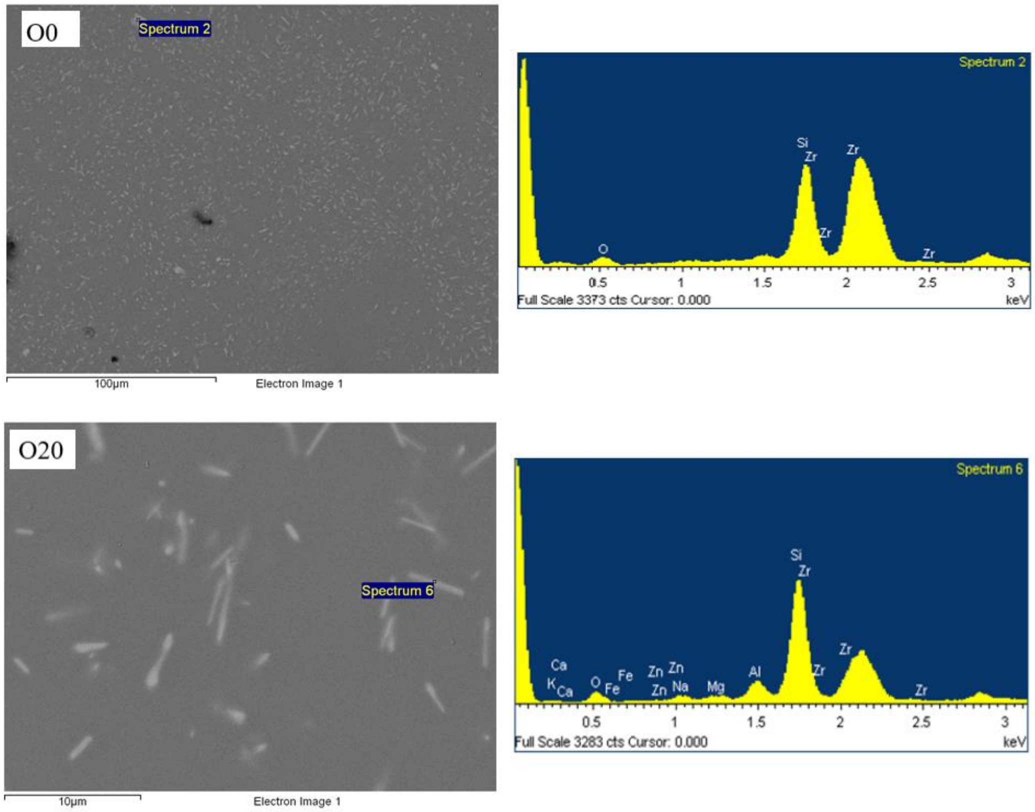


Figure 8. EDS spectra and spot analysis of glazed samples (O0 and O20)

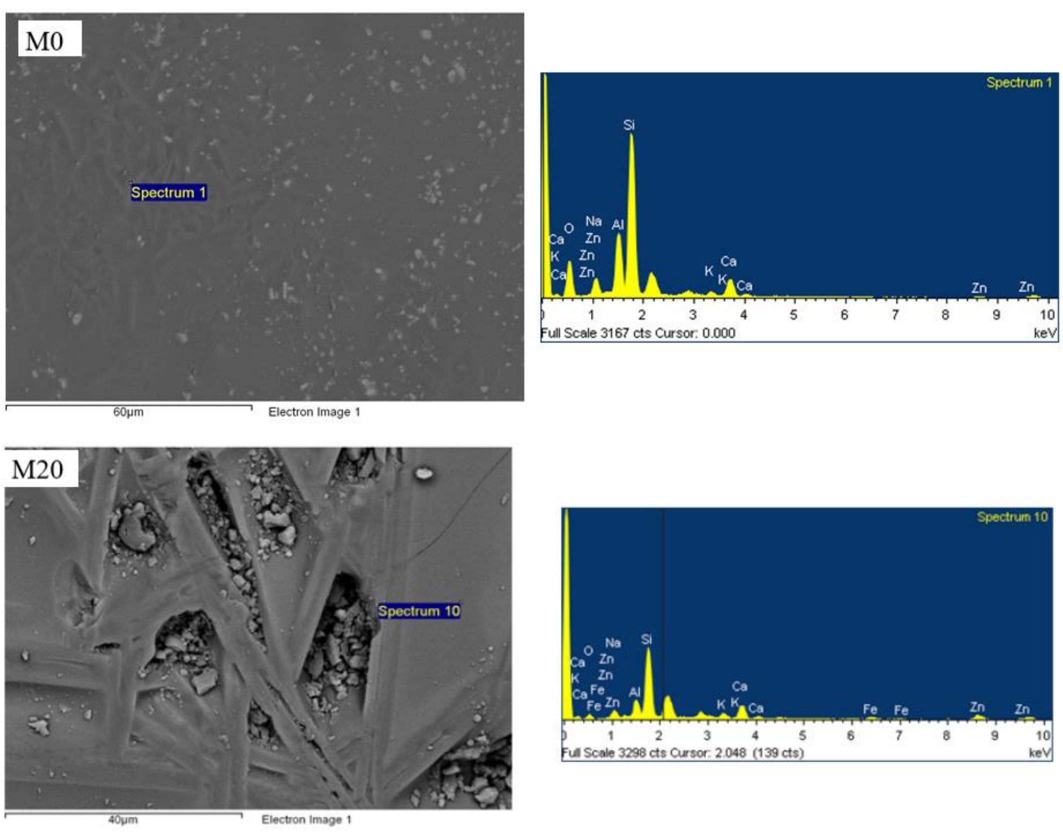


Figure 9. EDS spectra and spot analysis of glazed samples (M0 and M20)

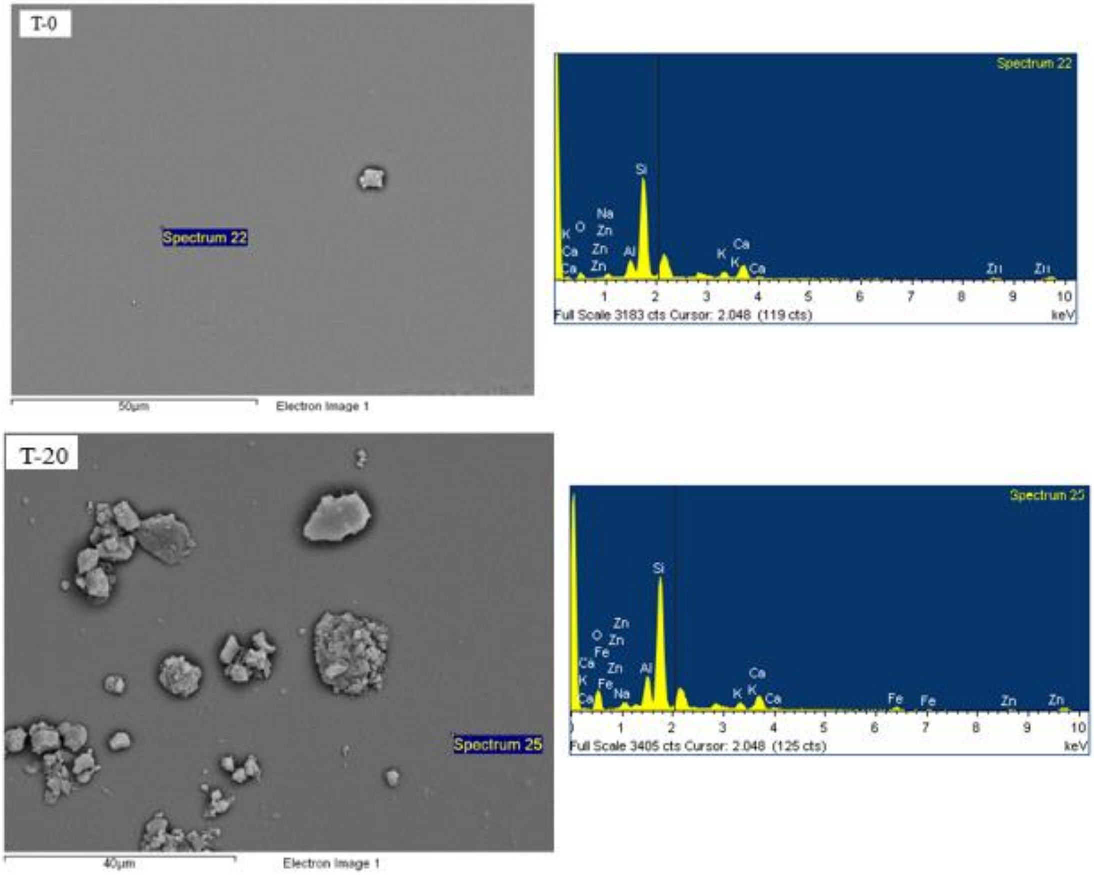


Figure 10. EDS spectra and spot analysis of glazed samples (T0 and T20)

4. Conclusions

The study aimed to investigate the impact of incorporating basalt-cutting waste into opaque, matt, and transparent glazes at various proportions. The addition of basalt-cutting waste resulted in the observation of yellow and beige shades in the glazed tiles. Due to the presence of iron oxide in the basalt-cutting waste, the L* values decreased as the waste content increased in all glaze types compared to standard opaque, matt, and transparent glazes. Conversely, the a* and b* values increased generally with higher proportions of basalt-cutting waste in the glazes. The presence of the coloring agent iron oxide in the basalt allowed the use of this material as a glaze coloring agent. The rest of the components of the basalt would contribute to the glaze matrix and with some frits the formation of anorthite was promoted.

Analysis of the phases formed in the glazed samples revealed that the opaque glazes contained zircon and quartz crystals, while the introduction of basalt-cutting waste led to the formation of anorthite crystals. The matt glazes exhibited anorthite and quartz crystals, with an increase in anorthite intensity when combined with basalt-cutting waste, accompanied by the formation of the diopside phase. The intensity of the amorphous phase increased in transparent glazes.

The SEM-EDS analysis of both opaque and transparent glazed tiles unveiled notable variations in their elemental composition. In the case of opaque glaze tiles, the presence of zircon crystals and anorthite phases showed marked distinctions between the standard and O20 samples. The inclusion of basalt-cutting waste led to the formation of needle-like anorthite crystals, a phenomenon previously documented in research. Furthermore, EDS analysis confirmed the existence of iron in the glassy phase of samples containing basalt waste, influencing color development, despite its absence in XRD analysis.

In transparent glaze tiles, differences in Si, O, Ca, Al, Zn, K, Na, and Fe content within the amorphous phase were evident when comparing standard and T20 samples. The higher iron content observed in the T20 was attributed to the incorporation of basalt waste. Based on the findings, it can be concluded that basalt-cutting waste can be economically utilized to produce yellow-beige pigments for different industrial ceramic glazes, depending on the glaze composition. The study sheds light on the potential of recycling the basalt-cutting waste in ceramic glaze production and expanding the range of color options available. This study provides valuable insights into the impact of basalt-cutting waste on the composition and microstructure of glazed tiles, offering significant implications for the ceramics industry.

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Procena upotrebe otpada pri sečenju bazalta u bojenju različitih kompozicija keramičkih glazura

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INFORMACIJE O RADU

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I Z V O D

Efekat bojenja kod keramičkih glazura ima presudnu ulogu u estetici i privlačnosti keramičkih predmeta. Pigmenti korišćeni u glazurama reaguju sa keramičkim materijalima tokom procesa pečenja, što kao rezultat daje spektar fascinantnih boja i efekata. Zahvaljujući prirodnim svojstvima bazalta kao što su čvrstoća na pritisak i otpornost na habanje, ovaj prirodni vulkanski kamen privlači mnogo pažnje kada se koristi u procesima proizvodnje keramike. Cilj ovog istraživanja je procena efekta otpada pri sečenju bazalta (BCW) iz Turske na efekat bojenja keramičkih glazura u kombinaciji sa različitim fritovima. U tu svrhu, pripremljene su glazure u koje je uključen BCW u različitim procentima težine od 0-20 % zajedno sa različitim fritovima. Kod glazura su ispitani hemijsko i termalno ponašanje, kao i faze. Za ispitivanje su korišćene sledeće tehnike: rendgenska fluorescencija (XRF), termalna mikroskopija i rendgenska difrakcija (XRD). Pripremljene glazure su zatim nanešene na engobirane zidne pločice i pečene na temperaturi od 1,200 °C u laboratorijskoj peći. Nakon pečenja, glazirane površine su podvrgnute analizi boja, dok je faza kompozicije analizirana XRD-om. Analiza mikrostrukture je izvršena korišćenjem elektronske mikroskopije (SEM/EDS). Povećanje udela BCW u kompozicijama glazura rezultiralo je promenom boje završenih površina sa krem do žućkasto-bež tonova. Ovo istraživanje pruža uvid u potencijalnu upotrebu BCW kao pigmenta u proizvodnji keramičkih glazura.

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