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Environmental Impact of Waste Biochar and Biomass Recycling in Sustainable Cement Composites. Analysis

Wpływ odpadowego biowęgla i recyklingu biomasy na środowisko w zrównoważonych kompozytach cementowych. Analiza

Iwona Ryłko, Wojciech Komala and Andrzej Białowiec*)

Keywords: *mineral waste; fly ash; biochar; pollutants' leachability; waste materials; biomass recycling; sustainable composites*

Abstract

This paper explores the technical and environmental benefits of using waste materials in cement production, such as reduced resource consumption, lower CO_2 emissions, and improved waste management. The potential of waste materials, including organic fibers and biomass biochar, as substitutes for traditional raw materials is explored, highlighting their ability to improve concrete properties and reduce production costs. However, challenges such as maintaining raw material consistency, meeting standards, and overcoming technological barriers need to be addressed. Therefore, the study aimed to investigate and analyze the potential of using biochar, biomass, and waste as a cement additive, taking into account environmental and technical aspects of waste recycling. The research and analysis carried out indicate that biomass fly ash, lignin, and biochar meet environmental and industrial standards. These materials do not cause hazardous emissions to the environment. From an economic point of view, the use of biochar, lignin, and biomass fly ash can lead to significant cost reductions in the construction industry by reducing the need for traditional raw materials in the cement industry. The study found that although waste materials offer significant environmental and economic benefits, their widespread adoption requires overcoming environmental and technological hurdles. In particular, biochar was identified as a promising material for the development of sustainable construction.

Słowa kluczowe: *odpady mineralne; popiół lotny; biowęgiel; wymywalność zanieczyszczeń; materiały odpadowe; recykling biomasy; zrównoważone kompozyty*

Streszczenie

Niniejszy dokument analizuje techniczne i środowiskowe korzyści płynące z wykorzystania materiałów odpadowych w produkcji cementu, takie jak mniejsze zużycie zasobów, niższa emisja CO_2 i lepsza gospodarka odpadami. Zbadano potencjał materiałów odpadowych, w tym włókien organicznych i biowęgla z biomasy, jako substytutów tradycyjnych surowców, podkreślając ich zdolność do poprawy właściwości betonu i obniżenia kosztów produkcji. Należy jednak stawić czoła wyzwaniom, takim jak utrzymanie spójności surowców, spełnianie norm i pokonywanie barier technologicznych. Dlatego też badanie miało na celu zbadanie i przeanalizowanie potencjału wykorzystania biowęgla, biomasy i odpadów jako dodatku do cementu z uwzględnieniem aspektów środowiskowych, technicznych i ekonomicznych. Przeprowadzone badania i analizy wskazują, że popioły lotne z biomasy, ligniny i biowęgla spełniają normy środowiskowe i przemysłowe. Materiały te nie powodują niebezpiecznych emisji do środowiska. Z ekonomicznego punktu widzenia wykorzystanie biowęgla, ligniny i popiołu z biomasy może prowadzić do znacznego obniżenia kosztów w budownictwie poprzez zmniejszenie zapotrzebowania na tradycyjne surowce w przemyśle cementowym. W badaniu stwierdzono, że chociaż materiały odpadowe oferują znaczące korzyści środowiskowe i ekonomiczne, ich powszechne przyjęcie wymaga pokonania przeszkód środowiskowych i technologicznych. W szczególności biowęgiel został zidentyfikowany jako obiecujący materiał do rozwoju zrównoważonego budownictwa.

Introduction

The cement industry is one of the key sectors for the economy, but also one of the most energy-intensive and emission-intensive. Cement production is responsible for approximately 7-8% of global carbon dioxide emissions, which is a significant challenge in the context of combating climate change. In Poland, which is one of the largest cement producers in the European Union, the sector plays a particularly important role, both from an economic and sustainable development perspective [33].

In recent years, the cement sector in Poland, as in other EU countries, has faced new environmental regulations stemming from efforts to achieve climate neutrality. The European Green Deal [61], presented by the European Commission in December 2019, forces high-emission industries – such as cement production – to make significant technological changes. In particular, the Carbon Border Adjustment Mechanism (CBAM) [14], due to come into force in 2026, and the expiry of free CO_2 emission allowances require the Polish cement industry to implement low-carbon technologies [13].

Poland is one of the largest cement producers in the European Union. According to the data of the Polish Association of Cement Producers, in 2020 the total production of cement in Poland amounted to 19.2 million tons [53]. The cement industry in Poland is represented

*) **Andrzej Białowiec,** Wrocław University of Environmental and Life Sciences, Department of Applied Bioeconomy, 37a Chełmońskiego Str., 51-630 Wrocław, Poland, andrzej.bialowiec@upwr.edu.pl; **Iwona Ryłko**, Wrocław University of Environmental and Life Sciences, Department of Applied Bioeconomy, 37a Chełmońskiego Str., 51-630 Wrocław, Poland, e – mail: iwona.rylko-polak@upwr.edu.pl; **Wojciech Komala,** Selena Industrial Technologies sp z o.o. sp. z o.o., Dzierżoniów, Poland, Pieszycka 1 58-200 Dzierzoniów, e-mail: wojciech.komala.selena.com; **Correspondence:** andrzej.bialowiec@upwr.edu.pl, +48713205973

by several large companies, including Lafarge Holcim, Heidelberg Cement, CRH, Cemex, and Górażdże Cement. These companies operate 13 cement plants located in different parts of the country [4]. Cement production in Poland is closely related to construction, which is one of the most important sectors of the Polish economy. The demand for cement in Poland is driven by the construction of new buildings, infrastructure projects, and the renovation and modernization of existing buildings, and the level of cement sale has been presented in Figure 1.

Cement production in Poland is subject to environmental regulations, and the industry is working to reduce its impact on the environment. The main challenges facing the industry include reducing carbon emissions, increasing energy efficiency, and reducing waste [45].

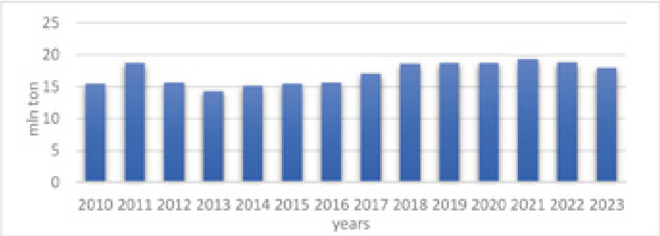


Fig. 1. Poland Central Statistical Office data on cement sales in Poland [45]

Rys. 1. Dane GUS dotyczące sprzedaży cementu w Polsce [45]

Key measures being taken by the industry are carbon capture and storage (CCUS) [15] technologies, increasing the share of low--carbon types of cement (CEM II – multi-component cement, CEM III – metallurgical cement), and increasing the share of renewable energy sources in production processes. One promising approach is also to incorporate waste materials into production processes, which can both reduce CO_2 emissions and improve the technical properties of the final products [9]. In particular, the use of biochar, which is a product of biomass pyrolysis, is attracting increasing interest in the context of building materials production [15].

Biochar has beneficial properties such as the ability to improve the structure of cement, increase its strength, and, at the same time, act as a carbon sequestering component. The use of this material is part of wider efforts to promote sustainability, reduce greenhouse gas emissions, and use renewable and waste raw materials in construction [20][44].

This paper aims to explore the potential of using biochar as a cement additive, taking into account both technical and environmental aspects. The effects of biochar on the strength properties of cement, its durability, and the sustainability of production in the context of reducing carbon emissions are analyzed. This research aims to provide a concrete response to the growing demand for sustainable building materials that meet contemporary regulatory and environmental requirements while maintaining high technical standards.

Mineral Waste in the Cement Industry

In 2021, Poland extracted 13.7 billion tons of rock minerals and 37 million tons of metallic minerals, as reported in the national balance of mineral resources [57]. These materials, once considered waste, are now valuable resources for substituting natural materials in building production [20]. The Act on Extractive Waste, updated in September 2021 [44], emphasizes waste prevention, impact reduction, and effective waste management, focusing on reduction, recovery, and disposal. A key recovery method is using mining waste in construction [57].

Poland's abundant resources include coal, gas, copper, and rock minerals. However, declining production and increased fossil fuel imports (coal by 75%, oil by 40%, and gas by 12% over 20 years) [19] highlight economic and environmental challenges. In 2021, extraction rates for metallic and chemical minerals continued to rise, with sulfur, rock salt, and barite extraction nearly doubling compared to previous years.

The war in Ukraine accelerated EU efforts to reduce dependence on Russian resources, boosting trade but exacerbating environmental pollution from transport. Developing green and low-carbon technologies is crucial [12].

Mineral raw materials are vital for cement properties like strength and durability. Key components include:

- Portland clinker (mainly calcium carbonate), forms essential binding minerals [17].
- Silica (quartz or amorphous), enhances strength and calcium silicate hydrate formation [6].
- Aluminum oxide (from bauxite or clay), aids early strength [2].
- Iron oxide (hematite/magnetite), adds color and strength [7].
- Gypsum (calcium sulfate), regulates setting time and prevents cracking [9].
- Pozzolanic materials (fly ash, silica dust), react with calcium hydroxide to improve durability and chemical resistance [10].
- Other additives (lime fillers, pozzolans), are tailored to achieve specific cement properties [28].
- Cement manufacturers carefully select mineral compositions to meet standards and regulations, ensuring materials are environmentally safe and inert, with low pollutant elution levels [60].

Fly Ash and Bottom Ash with Slag from the Biomass Combustion Properties

Another source of waste, that can be added to the cement recipes, maybe fly ash from power plants [41] Because the Polish energy system is mostly based on bitumen and lignite coal combustion, flay ashes are produced in large amounts. Every year, Polish power plants produce over 20 million tons of by-products from the combustion of hard coal and brown coal. However, recent trends in the transition from fossil fuels to biomass show that biomass combustion contribution in the energy sector will increase, reaching 17% in 2021 [41]. Therefore, fly ash, as a new type of mineral waste on the market, has been chosen as an additive for cement. The application of fly ash from biomass incineration may bring the following benefits:

- Fly ash from biomass combustion represents a byproduct that can be effectively utilized, reducing and thereby reducing the environmental impact associated with its disposal. This aligns with the principles of sustainable development by promoting waste reduction and reuse [8].
- Biomass-derived fly ash typically has a lower carbon content compared to coal fly ash. By incorporating it into cement products, the overall carbon footprint of the construction material is reduced. This supports efforts to mitigate climate change and promote eco-friendly construction practices [49].
- Biomass fly ash can contribute to the improved compressive strength and durability of concrete. It may act as a pozzolanic material, reacting with calcium hydroxide in the cement to form additional cementitious compounds, resulting in a more durable and resilient final product [42][47].
- The use of biomass-derived fly ash may offer advantages in terms of regulatory compliance, especially in regions where there are restrictions or concerns related to the use of traditional coal fly ash. Biomass fly ash is generally considered to be a more environmentally friendly alternative [59][1].

Biochar

Recently, biochar has emerged as a promising cement additive [56] with several potential benefits including carbon sequestration, as biochar captures carbon and helps reduce greenhouse gas emissions, supporting climate change mitigation efforts [56]. By partially replacing Portland cement, biochar reduces the demand for energy-intensive cementitious materials, thereby lowering the overall environmental footprint [56][54]. Biochar also offers thermal insulation, enhancing the energy efficiency of concrete structures, which is crucial for temperature regulation in construction. Additionally, biochar can improve the compressive strength and durability of concrete, acting as a pozzolanic material that reacts with calcium hydroxide to form additional cementitious compounds [54]. It is produced from agricultural residues and forestry by-products, which promotes waste reduction and sustainable resource use. Research supports biochar's role in enhancing the mechanical and environmental performance of concrete, reducing CO_2 emissions, and advancing construction sustainability, aligning with the objectives of this article [36][62]. However, potential environmental concerns such as pollutant elution upon water contact need to be further studied, especially given the exposure of structures to harsh weather conditions. This paper examines waste raw materials from mineral and industrial sources, considering the risks of pollutant elution and their potential impact on construction [33].

Organic Waste in the Cement Industry

Organic waste, particularly from the agri-food sector, includes biodegradable materials such as crop residues, food waste, and animal manure [16]. Transitioning to a circular economy is essential for minimizing waste and enhancing recycling processes [21]. In 2021, Poland generated 121 million tons of waste, with municipal waste making up 11.3% (13.7 million tons), a slight decrease from the previous year [43].

Using organic waste as an alternative raw material for eco-concrete production presents environmental benefits, such as reducing landfill waste, lowering greenhouse gas emissions, and decreasing cement use, thus mitigating the carbon footprint of concrete [43]. Examples of suitable organic waste include sawdust, rice husk ash, straw, and agricultural residues, which can partially replace cement or aggregates while enhancing concrete properties like strength and durability [32].

Natural-origin materials, such as recycled nylon fibers, bamboo, hemp, jute, and lignin, are renewable and biodegradable, aligning with sustainable building trends and advanced processing technologies [32]. Though still experimental, early research suggests that organic waste holds promise as a sustainable alternative in concrete production.

Natural and Recycled Fibers

Natural plant fibers are lightweight, biodegradable, and have wave-suppressing properties, making them a sustainable alternative to synthetic fibers. Common sources include hemp, flax, sisal, jute, coconut, bamboo, agave, and palm, with fibers obtained from stems, leaves, and seeds. Recently, fibers from agri-food waste have gained attention, primarily consisting of cellulose, hemicellulose, and lignin [50][29].

Bamboo Fibers

Bamboo, a rapidly growing and eco-friendly plant, is used in various industries, from construction to cosmetics. With about 1,000 species, bamboo fibers are extracted mechanically or chemically. Mechanical methods yield strong, short fibers using low energy, while chemical processes, such as hydrolysis, modify fiber properties by removing lignin and other components. China is a major producer, employing advanced fiber production techniques [26][34][63].

Waste Lignin

Lignin, a major component of wood, is used in construction as a binder and dispersant. It makes up 24-28% of dry wood mass and binds cellulose fibers in trees. During wood processing, lignin-based by-products, like sodium lignosulfonates, are produced through sulfite pulping in the paper and wood industries. These by-products are valuable as concrete admixtures due to their structural properties [37][23].

Pollutant elution from waste in the context of waste recycling

Regulation of the Minister of Economy of 16 July 2015 on the release of waste to landfills [24]. Contain limits and limits for potentially present chemicals in waste. The study of the leaching of contaminants in waste in the context of the production of cementitious products is an important aspect from the point of view of environmental protection and compliance with landfill regulations. The significance of such a study lies in the fact that it makes it possible to determine the potential risks to the environment and public health resulting from the presence of contaminants in waste that is used as raw materials or fuels in the production of cementitious products. A pollutant leaching test can help determine whether the use of certain types of waste is safe and following applicable standards [24]. The spectrum that is evaluated in the contaminant leaching test in the context of cementitious product production includes:

- chemical composition of waste – the test determines what chemicals are present in the waste and in what quantities. This is important because some substances can be toxic or can affect the quality of cementitious products [55].
- contaminant leachability – the study evaluates how contaminants can be released from waste during the cement production process or as a result of interaction with water or other agents [22].

The significance of this research arises from the need to guarantee the safe and ecological utilization of waste in cement production and conformity with environmental protection regulations and standards. Additionally, this research aids cement manufacturers in identifying possible issues and implementing effective corrective measures to minimize harm to the environment and human health [22].

Therefore, the study aims to identify the pollutants elution from chosen types of biowaste during contact with water in the context of analyses of biowaste recallability in concrete products.

Materials and Methods

Sources of the collected Mineral Waste Materials

The tested waste was obtained directly from producers or suppliers:

- Fly ash from biomass combustion from the Enea Połaniec CHP Plant, Poland. Two types of ashes were collected:
- bottom ash with slag,
- fly ash from biomass combustion

Biochar

Biochar – obtained from the pyrolysis of fruit wood chips (apple tree, pear). The pyrolysis process occurred in a Snol 8.2/1100 LFMOR muffle furnace under an inert atmosphere of CO_2 at a temperature of 500 °C for 1 h in the laboratory of the Department of Applied Bioeconomy, Wrocław University of Environmental and Life Sciences, Poland. Initially, the biomass was dried to remove moisture to facilitate further decomposition. The biomass was gradually heated to the desired pyrolysis temperature. At higher temperatures, thermal decomposition reactions took place, leading to the breakdown of complex organic compounds in the wood into simpler molecules. Gases such as hydrogen, methane, carbon monoxide, and carbon dioxide were formed, as well as liquid pyrolytic products such as tar, oils, and organic acids. The solid product was biochar, which is rich in carbon [5].

Sources of collected organic waste for testing

Four types of biowaste had been chosen for planned experiments: bamboo fibers, hemp fibers, fibers from recycled textiles, and lignin. The collected biowaste was obtained directly from producers or suppliers:

- The bamboo fibers were supplied by RETTENMAIER Polska Sp. z o.o, one of the largest fiber suppliers in Europe.
- Lignin derivative – sodium lignosulfanate lignin content: 58%; manufacturer – Proexport Chemicals.

Methods for Raw Material Properties Determination

The important properties of materials used in construction chemicals include bulk density, moisture content, absorbability/hydrophobicity, electric conductivity, pH, ash content, higher heating value, lower heating value, and elemental composition – C, H, N, S, O. These properties are important for the proper selection and use of materials in various applications.

Bulk density is the mass of the material per unit volume, including both solid and empty spaces, and is typically determined using a volumetric meter [5].

Moisture content refers to the amount of water present in the material and can affect its performance and properties [27][40]. To determine the moisture content of the tested materials, the MA50R moisture analyzer (Ragwag, Poland) was used.

Absorbability/hydrophobicity is measured using the water drop penetration time method and indicates the material's ability to absorb water [30]. Absorbency and hydrophobicity testing was conducted using the water drop penetration time (WDPT) method [30].

The electrical conductivity and pH of the material were measured by dissolving the test material in water at a ratio of 1:10 (organic material to water) using the IJ-44A electrode and ECF-1 sensor. The conductivity and pH of the solutions were used for the tests [43].

The ash content [58] of the material was determined by the complete combustion of 1-2g of the analytical sample weight in a muffle furnace at 815±15°C and calcination of the remaining ash using the SNOL 8.2/1100 (LSM01, Poland) furnace. The specific ash content was determined using laboratory analysis with the standard method BN-796048-02.02.

The higher heating value (Qs) and lower heating value (Q) can be determined by laboratory analysis using methods such as bomb calorimetry [18]. The analysis of the raw materials was conducted using a calorimetric bomb (IKAC200, Poland) in an oxygen atmosphere at 25°C.

The parameters characterizing the elemental composition of the materials, such as C, H, O, N, and S [11], were obtained using the Perkin Elmer PE2400 series II CHNS/O analyzer.

Methods for Determining Pollutant Elution from Raw Materials

To assess the leachability of pollutants from waste raw materials, a leaching test was conducted based on the Regulation of the Minister of Economy of 16 July 2015 on the admission of waste to landfills [56]. The test was performed according to PN-EN 12457-4:2006, and the water extracts obtained were analyzed for indicators of pollution according to PN-EN ISO/IEC 17025. The aforesaid leaching test provides for one-step leaching of water-soluble components under static conditions. The extraction time is 24 hours, including 6 of intensive stirring and 18 hours of rest testing [26]. After the extraction time, the liquid solution was separated on 0.45 mm paper filters. The obtained aqueous extracts were subjected to analytical tests to determine the following pollution indicators Ba, Cd, Cr, Cu, Hg, Mo, Ni, Pb, Zn, Se, Sb, As, Cl, F, S, dissolved organic carbon (DOC), total dissolved solids (TDS).

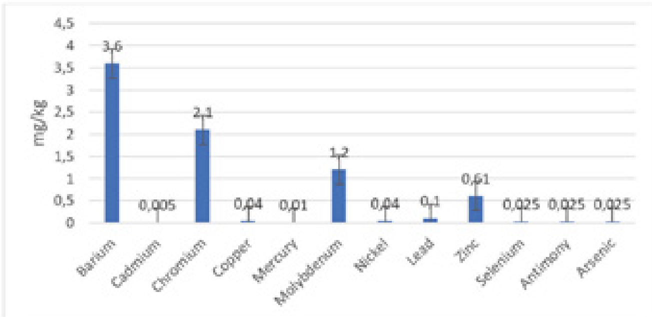
Fly Ash and Bottom Ash with Slag from the Biomass Combustion Properties

The analysis covered two types of waste, fly ash from biomass combustion, waste with the waste code 10 01 01, formed in a fluidized bed boiler, formed in the process of burning 100% biomass, without the participation of coal dust; and formed during biomass combustion and discharged from the bed of bottom sand/ash with slag with waste code 10 01 24. Results are given in Table 1.

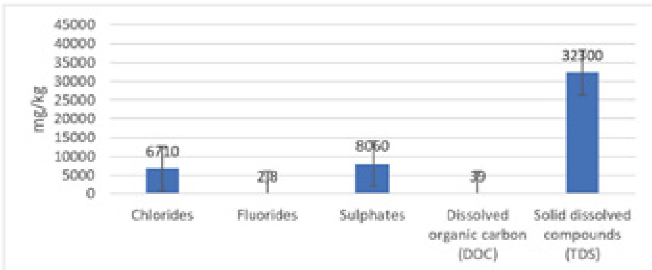
Table1. Properties of fly ashes and bottom ash

Tabela1. Właściwości popiołów lotnych i dennych

Parameters	Unit of measurement	Results	
		Fly ash from the biomass	Bottom ash with slag
		10 01 01	**10 01 24**
Density	kg/m^3	500	1300
Reaction	pH	12.5	11.0
Water content	%	0.0	0.025
Electric conductivity	mS/cm	14.35	0.7
Higher heating value	J/g	17570	-
Ash content	%dm	99,94	99,91
Organic content	%dm	0.06	0.09
C carbon	%dm	47.00	1.62
H hydrogen	%dm	0.55	0.50
N nitrogen	%dm	0.55	0.20
S sulphur	%dm	2.00	0.75
O oxygen	%dm	49.9	96.93



Requirement values from the regulation *	Ba	Cd	Cr	Cu	Hg	Mo	Ni	Pb	Zn	Se	Sb	As
	≤100	≤1	≤10	≤50	≤0,2	≤10	≤10	≤10	≤50	≤0,5	≤0,7	≤2



Requirement values from the regulation *	Cl	F	S	DOC	TDS
	≤15000	≤150	≤20000	≤800	≤60000

Fig 2. Pollutant elution rate (mg/kg) from the fly ash from biomass.*

** – regulation of the Minister of Economy dated July 16, 2015 [26] on the receipt of inert waste into the landfill, Appendix 2*

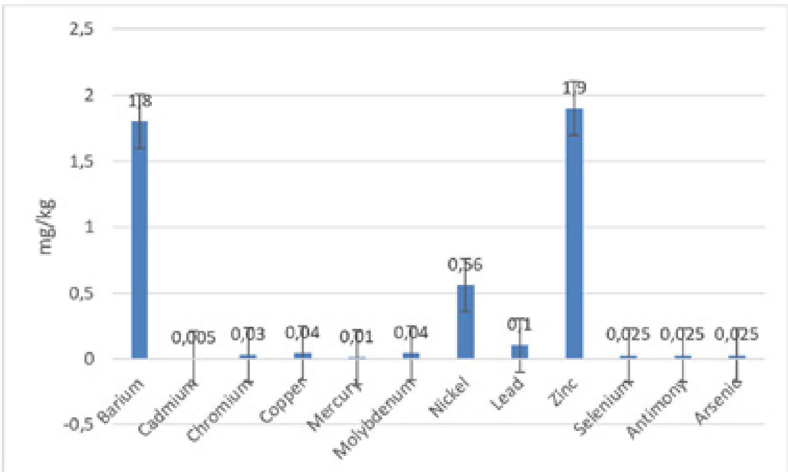
Rys. 2. Stopień wymywania zanieczyszczeń (mg/kg) z popiołu lotnego z biomasy.

** – rozporządzenie Ministra Gospodarki z dnia 16 lipca 2015 r. [26] w sprawie przyjmowania odpadów obojętnych na składowisko, Załącznik 2*

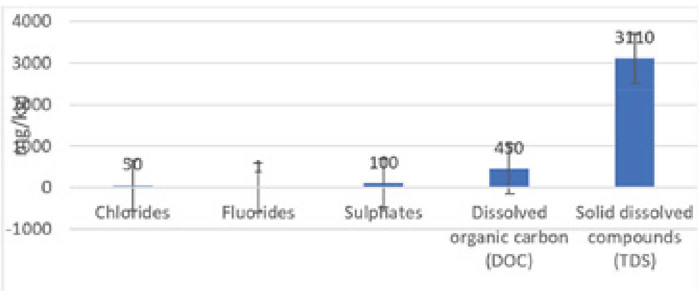
Fly ash (waste code 10 01 01) from fluidized bed biomass combustion and bottom ash with slag (waste code 10 01 24) were assessed. Fly ash had a bulk density of 500 kg/m³ and pH of 12.5, while bottom ash had a higher density of 1300 kg/m³ and pH of 11.0. Fly ash showed high electrical conductivity (14.35 mS/cm), but bottom ash was much lower (0.7 mS/cm). The carbon content in fly ash was notably high (47%), suggesting a significant presence of unburned carbon, mostly in carbonate form. The low hydrogen content supports this interpretation. The grain size of bottom ash, with slag inclusions up to 1 cm, made it unsuitable for construction chemicals without additional processing. Fly ash, however, met regulatory standards for inert waste and is considered suitable for cement mixtures, supporting the recycling of biomass ash in construction [24].

Biochar

The tested biochar had a dark color and a bulk density of 150-250 kg/m³. The raw material was characterized by an alkaline pH of 9.3. It had strong hydrophobic properties; the moisture content was low 0.4%. Biochar contains combustible parts of about 10%, and the rest is an organic part. The higher heating value for the tested raw material was 30294 J/g, and the electric conductivity was 0.672 mS/cm (Tab. 2).



Requirement values from theregulation *	Ba	Cd	Cr	Cu	Hg	Mo	Ni	Pb	Zn	Se	Sb	As
	≤100	≤1	≤10	≤50	≤0,2	≤10	≤10	≤10	≤50	≤0,5	≤0,7	≤2



Requirement values from the regulation*	Cl	F	S	DOC	TDS
	≤15000	≤150	≤20000	≤800	≤60000

Fig. 3. Pollutant elution rate (mg/kg) from the biochar.
** – regulation of Minister of Economy dated July 16, 2015 [26] on the receipt of inert waste into the landfill, Appendix 2*

Rys. 3. Stopień wymywania zanieczyszczeń (mg/kg) z biowęgla.
** – rozporządzenie Ministra Gospodarki z dnia 16 lipca 2015 r. [26] w sprawie przyjmowania odpadów obojętnych na składowisko, Załącznik 2*

Table 2. The properties of biochar
Tabela 2. Właściwości biowęgla

Parameters	Unit of measurement	Results
Density	kg/m³	150-250
Reaction	pH	9.3
Water content	%	0.4
Electric conductivity	mS/cm	0.672
Heat of combustion	J/g	30294
Ash content	%dm	10
Organic content	%dm	90
C carbon	%dm	70.00
H hydrogen	%dm	2.50
N nitrogen	%dm	0.60
S sulphur	%dm	0.05
O oxygen	%dm	26.85

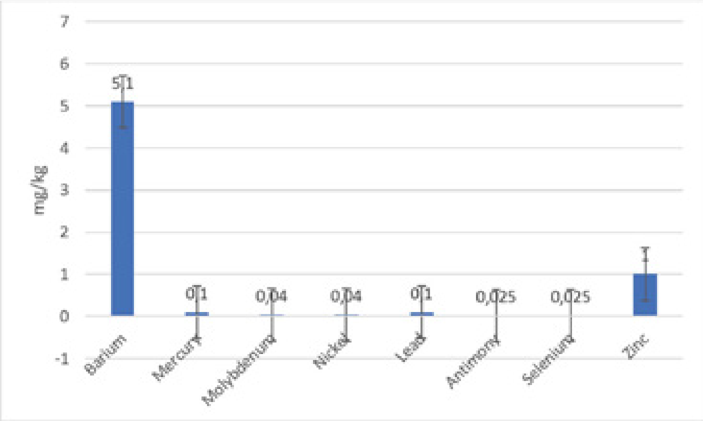
Biochar, with a dark color and bulk density of 150-250 kg/m³, displayed an alkaline pH (9.3), low moisture content (0.4%), and high organic carbon content (70%). It had hydrophobic properties and a high heating value of 30,294 J/g. The environmental assessment confirmed its inert status, making it a viable additive for cement, reducing the environmental impact of construction and enhancing mortar properties [24].

Natural fibers — bamboo fibers

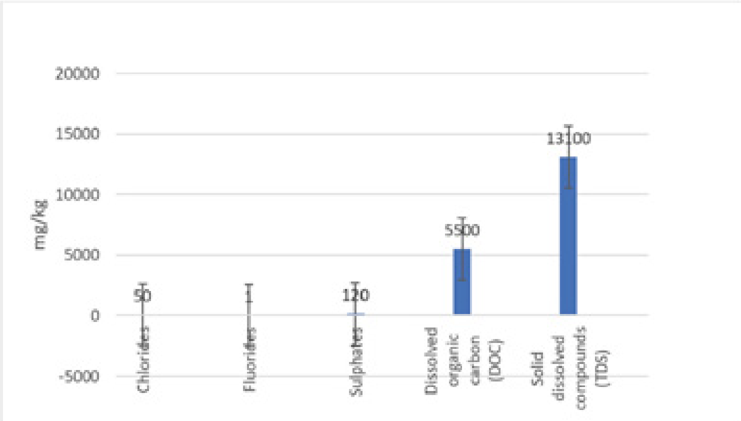
The tested fiber is characterized by a low bulk density of 0.6-1.1 g/cm3, contains about 6%, moisture, and is a hydrophilic material. pH is quite alkaline about 9. Electric conductivity is about 242 µS/cm, and its heat of combustion is 17570 J/g. The ash content was also measured and the results range from about 1.7 — 5%, bamboo fiber is an organic material, where the content of organic parts is about 95 – 99%. The carbon content was on average 46%, hydrogen 5.60%, nitrogen about 0.5%, and sulfur about 1.2% (Tab. 3).

Table 3. The properties of bamboo fibers
Tabela 3. Właściwości włókien bambusowych

Parameters	Unit of measurement	Results
Bulk density	g/cm3	0.6 – 1.1
Reaction	pH	9
Water content	%	6,2
Electric conductivity	µS/cm	242
Heat of combustion	J/g	17570
Ash content	%	1.7 – 5.0
Organic content	%	95 – 99
Elemental analysis		
C carbon	%	46
H hydrogen	%	5.60
N nitrogen	%	0.5
S sulphur	%	1.2
O oxygen	%	46,7

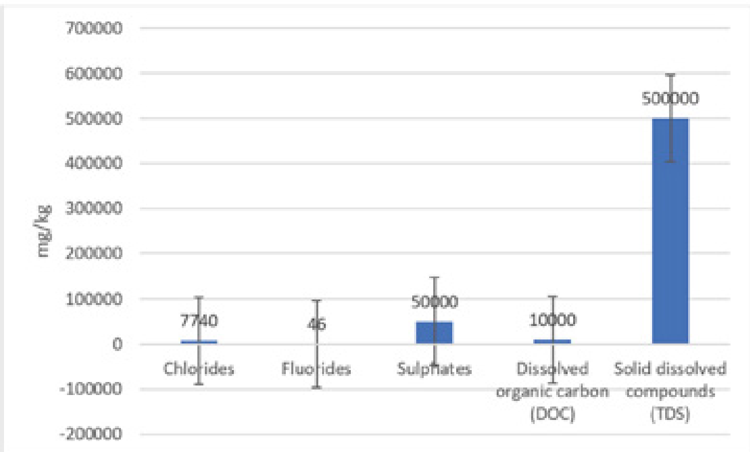


Requirements from regulation*	Ba	Hg	Mo	Ni	Pb	Zn	Se	Sb
	≤100	≤0,2	≤10	≤10	≤10	≤50	≤0,5	≤0,7



Requirements from regulation*	Cl	F	S	DOC	TDS
	≤15000	≤150	≤20000	≤800	≤60000

Fig. 4. Pollutant elution rate (mg/kg) from bamboo fibers
** – regulation Minister of Economy dated July 16, 2015 [26] on the receipt of inert waste into the landfill, Appendix 2*
Rys. 4. Stopień wymywania zanieczyszczeń (mg/kg) z włókien bambusowych
** – rozporządzenie Ministra Gospodarki z dnia 16 lipca 2015 r. [26] w sprawie przyjmowania odpadów obojętnych na składowisko, Załącznik 2*



Requirements from regulation*	Cl	F	S	DOC	TDS
	≤15000	≤150	≤20000	≤800	≤60000

Fig. 5. Pollutant elution rate (mg/kg) from lignin
** – regulation Minister of Economy dated July 16, 2015 [40] on the receipt of inert waste into the landfill, Appendix 2*
Rys. 5. Stopień wymywania zanieczyszczeń (mg/kg) z ligniny
** – rozporządzenie Ministra Gospodarki z dnia 16 lipca 2015 r. [40] w sprawie przyjmowania odpadów obojętnych na składowisko, Załącznik 2*

Organic Polymer – Lignin

Sodium lignosulfonate, derived from wood pulping, was tested for use in cement.

The raw material has a moisture content of about 5%, is soluble in water, and has a pH is 5. Raw material density: 0,25 g/cm3. The electric conductivity is 372 µS/cm and the heat of combustion is 19016 J/g. The content of combustible parts is about 13%, organic parts are 72%. Carbon content is about 60%, hydrogen 6.3%, nitrogen 0.45%, and sulfur about 6% (Tab. 4).

Table 4. Properties of lignin
Tabela 4. Właściwości ligniny

Parameters	Unit of measurement	Results
Density	g/cm^3	0,25
Reaction	pH	5
Water content	%	5
Electric conductivity	µS/cm	372
Heat of combustion	J/g	19016
Ash content	%	13
Organic content	%	72
Elemental analysis		
C carbon	%	60
H hydrogen	%	6.3
N nitrogen	%	0.45
S sulphur	%	6

The lignin tested did not mineralize, meaning its mineral components could not be easily broken down, making standard metal content analysis ineffective. This could be due to stable crystalline structures, low solubility, or slow reactivity with chemical agents. Additionally, the sulfate, DOC, and TDS levels exceeded regulatory limits, classifying the material as hazardous waste. Consequently, this lignin derivative cannot be used in new concrete formulations. However, lignin's potential benefits, such as reducing CO_2 emissions, substituting traditional cement components, and minimizing wood waste, justify sourcing cleaner alternatives[48][52]. Continued research is crucial to harness lignin's potential and promote sustainable practices in the cement industry.

Summary of tests

Industrial waste can serve as a sustainable component in concrete, offering environmental and economic benefits when used appropriately. Fly ash, whether from coal or biomass combustion, can enhance concrete's strength and durability due to its reactive silica and alumina. However, biomass fly ash has unique challenges, including higher carbon and volatile content, which may affect setting time and lead to potential alkali-silica reactions. Thus, careful assessment of its composition and compatibility is crucial. Despite variability in quality, biomass fly ash shows promise, providing benefits like reduced cement use and improved workability, provided it meets quality standards.

Biochar, produced from organic biomass, stands out for its environmental advantages. It can sequester carbon, reduce cement consumption, improve workability and strength, and enhance thermal insulation. Key considerations include particle size, dosage, and compatibility with cement. Continued research is necessary to optimize its use and develop clear guidelines.

Utilizing these waste materials in construction helps lower environmental impact, reduce cement reliance, and promote waste recycling. However, rigorous testing is essential to ensure compliance with standards. By integrating materials like fly ash, biochar, and other industrial waste, the construction sector can move toward a more eco-friendly and cost-effective approach, addressing both environmental concerns and regulatory demands [52][38].

Challenges and Trends in Reducing CO_2 Emissions in the Cement Industry

Europe's efforts to curb carbon emissions are central to the Green Deal, which has driven regulatory changes, investments in renewable energy, and a focus on energy efficiency. CO_2 emissions have generally been on the decline, with an 8% drop in 2023 compared to 2022. However, challenges persist, particularly in the transportation sector, where emissions continue to rise, and in high-emission industries such as cement production. In Poland, cement production contributed 9 million tonnes of CO_2 emissions in 2021, representing about 3% of the nation's total. Although emissions from this sector have dropped by 15% since 1990, further reductions are critical[38].

Trends and Innovative Solutions

Reducing CO_2 emissions from cement production involves several innovative approaches. The use of low-carbon technologies, such as carbon capture and storage (CCS), alternative fuels, and more efficient production processes, are essential. Additionally, waste materials are gaining attention as substitutes for traditional raw materials. For example, biomass fly ash can replace up to 40% of clinker cement, reducing emissions by 30% and conserving natural resources. Waste organic fibers and biochar are also being explored for their ability to enhance concrete properties while lowering environmental impact. Biochar, in particular, holds promise due to its carbon sequestration potential, improved thermal insulation, and ability to lower cement use [3][31].

Higher-Level Research and Development

These trends align closely with higher research goals in sustainable construction. Advanced studies are focusing on optimizing the use of waste materials, improving the consistency and quality of industrial by-products, and developing new processing technologies to make these solutions more efficient and cost-effective. Research is also crucial in understanding the long-term impact of these materials on concrete performance, environmental safety, and economic viability. The integration of biochar, fly ash, and organic fibers into cement systems is part of a broader strategy to create a circular economy and support climate neutrality goals.

By addressing these challenges through interdisciplinary research and innovation, the cement industry can transform into a more sustainable sector, meeting both environmental regulations and market demands for eco-friendly construction materials. Collaboration between academia, industry, and policymakers will be essential to accelerate this transition and maximize the potential of waste-based cementitious products[51].

Summary

The drive for environmental protection and sustainability has led to the development of regulations, particularly in waste management within the construction industry. Incorporating waste materials into building production reduces the demand for raw resources like sand and cement, cuts energy use, lowers costs, and supports eco-friendly building practices. Waste recycling helps reduce landfill burdens and pollution risks, aligning with sustainable goals.

Research on waste, biomass, and biochar demonstrates that fly ash from biomass, lignin, and biochar meet industry standards, showing favorable density, strength, and durability, which contribute to the overall structural integrity of building materials. Laboratory analyses confirmed that the fly ash is free from harmful substances, ensuring safe use, while leachability tests verify no hazardous environmental emissions.

The use of biochar, lignin, and biomass ash can lead to significant cost reductions in construction by lowering the need for traditional raw materials such as cement and aggregates. Additionally, energy savings during production reduce operational costs and contribute to more sustainable, cost-efficient processes. The integration of these materials not only promotes compliance with environmental certifications like LEED and BREEAM but also offers a financially viable path toward more eco-friendly construction practices, aligning with long-term sustainability goals in the industry.

Author Contributions

"Conceptualization, A.B. and I.R.; methodology, A.B. and I.R.; validation, A.B. and I.R..; formal analysis, I.R. investigation, I.R.; resources, I.R.; data curation, I.R.; writ-ing—original draft preparation, I.R.; writing—review and editing, A.B. and I.R.; visualization, I.R.; supervision, A.B.; project administration, A.B.; funding acquisition, A.B. and I.R.

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Conflicts of Interest

The authors declare no conflicts of interest.

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