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RECENZOVANÝ ČASOPIS PRO VÝSLEDKY VÝZKUMU A VÝVOJE Z OBLASTI PRŮMYSLOVÉ A KOMUNÁLNÍ EKOLOGIE

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ODPADOVÉ FORUM 2025 (14. – 16. 10. 2025, Hustopeče)

symposium pro výsledky výzkumu a vývoje pro průmyslovou a komunální ekologii

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Vážení čtenáři,

máte před sebou první číslo již 18. ročníku časopisu WASTE FORUM. Jak jsme předem avizovali, je to tematické číslo na téma VEDLEJŠÍ PRODUKTY A ODPADY Z POTRAVINÁŘSTVÍ. Toto téma navazuje na konferenci Potravinářství na cestě k udržitelnosti, která se spolu se symposiem ODPADOVÉ FORUM 2024 konala loni v listopadu. Část článků jsou rozšířené texty přednášek ze zmíněné konference, další přišly do redakce v reakci na úspěch konference.

Tak, jak je u nás zvykem, číslo není čistě monotematické, protože by bylo škoda odkládat zveřejnění jinak zaměřených článků až do dalšího čísla.

Patronem čísla je letošní ročník symposia ODPADOVÉ FORUM 2025 (14. – 16. 10., Hustopeče), jehož 1. cirkulář (Call for papers) najdete na konci tohoto čísla. Symposium se od počátku v roce 2006 konávalo vždy na jaře (nejprve v dubnu, později v březnu), ale v době covidu jsme museli nejprve jeden ročník vynechat a poté přejít na podzimní termín.

Při tom jsme hledali měsíc, který by z organizačního pohledu vyhovoval co nejvíce (říjen, září, listopad a nakonec zase říjen), až jsme se rozhodli, že se vrátíme k osvědčenému jarnímu termínu. Ale jak na to? Vynechat jeden rok, nebo udělat dva ročníky za sebou s jen půlroční pauzou?

Rozhodli jsme se pro druhou variantu s tím, že termín dalšího ročníku vyhlašujeme již nyní, aby si přednášející mohli vybrat, který termín jim lépe vyhovuje. Tedy symposium ODPADOVÉ FORUM 2026 se bude konat 24. – 26. 3. 2026 na stejném místě jako v posledních X letech, tedy v Hustopečích.

I když oba ročníky symposia budou pokrývat celou širokou oblast průmyslové a komunální ekologie, zvolili jsme pro tyto dva krátce po sobě konající se ročníky po třech zvýrazněnzých tématech. Ale zdůrazňuji, zvýrazněná témata neznamenají tematické zúžení daného ročníku symposia, jen pomoc řešitelům takto zaměřených projektů, který ročník si vybrat, pokud jim jinak termínově vyhovují oba.

Pro letošní ročník 2025 to jsou ODPADY ZEA PRO STAVEBNICTVÍ (návrat k osvědčenému tématu z ročníku 2023), OEEZ A ODPADY Z ELEKTROPRŮMYSLU a ODPADNÍ TEXTIL. Více v pozvánce na konci tohoto čísla.

Pro symposium ODPADOVÉ FORUM 2026 jsme pak jako zvýrazněná témata zvolili POTRAVINÁŘSTVÍ NA CESTĚ K UDRŽITELNOSTI jako reakci na úspěch loňské stejnojmenné konference), MATERIÁLY ZE ZPRACOVÁNÍ AUTOVRAKŮ A ODPADY Z AUTOMOTIVE a PRŮMYSLOVÉ ODPADNÍ VODY.

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Uzávěrka nejbližšího čísla časopisu WASTE FORUM je 8. dubna 2025, další pak 8. července 2025.

For authors

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The deadline of the next issue is on April 8, 2025, more on July 8, 2025.

Valorization of Chicken Deboner Residues: Gelatin Extraction and its Application for Jellies and Films

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Summary

In recent decades, global food industry waste has significantly increased, with food waste categorized into human consumption and non-edible industrial by-products, including animal by-products. This study aims to reduce these by-products by repurposing chicken tissue for gelatin extraction. The gelatin extraction process from mechanically deboned chicken meat residues was optimized using food enzymes, and the physicochemical and rheological properties of the gelatins were analyzed. Temperature and extraction time, as independent factors, were examined using the Taguchi experimental design. Under optimal conditions, the resulting gelatins exhibited high gel strength (196 – 353 Bloom) and viscosity (3.2 – 7.6 mPa·s), making them suitable for gelling agents in jelly confectioneries. Furthermore, low Bloom-value chicken gelatins were used to create edible films, and tests on their sorption and desorption behavior revealed temperature- and humidity-dependent characteristics, with improved plasticity and reduced sorption hysteresis at higher temperatures. This environmentally friendly processing technology for mechanically deboned chicken meat residues aligns with zero-waste principles.

***Keywords**: animal by-products, gelatin, gelling properties, yield, surface properties, mechanically deboned chicken meat residue, multi-stage extraction, sorption isotherms, films, jelly*

Introduction

Two significant issues currently facing developed countries are the high level of food waste and the increase in animal husbandry, both of which have significant environmental impacts. Addressing these problems is essential for the planet's and its inhabitants' well-being.

Animal production and consumption contribute to increased greenhouse gas emissions (GHGEs), land use and degradation, water scarcity, nutrient pollution (e.g., acidification and eutrophication), the use of fertilizers and pesticides, and food waste along the entire supply chain, which exacerbates climate change and leads to further environmental deterioration, such as natural disasters, habitat and biodiversity loss, and freshwater scarcity in food systems.[1]

The most significant portion of food waste comprises vegetables and fruits (39%), followed by dairy products (17%) and meat (14%). In the European Union, nearly one-third of food produced for human consumption is wasted annually.[2] Discarding food also wastes the water, energy, and labor invested in growing, processing, packaging, and transporting it while increasing GHGEs, eutrophication, cropland use, and disposal costs.[1] Besides food waste intended for human consumption, other types of waste are not edible for humans. This summary will focus on a specific kind of inedible food waste: animal by-products (ABPs), specifically chicken deboner residues (CDRs), which are primarily generated in slaughterhouses during meat production and can be further processed into high-quality, protein-rich products such as gelatin. The reusage of these ABPs promotes the reduction of food waste and provides new potential for the sustainable food industry.[3,4]

Poultry meat consumption continues to grow, with projections indicating an increase to 12,568 million tons by 2033 (currently around 12,386 million tons), leading to a rise in the production of high-protein ABPs.[5] In 2021, 677,200 tons of gelatin were produced from pork and beef. It is anticipated that the consumption of gelatin will increase by 8% annually. By 2035, porcine and bovine gelatin production is expected to be insufficient to meet global demand, making the production of gelatin from alternative collagen sources desirable. Prioritizing the valorization of animal by-products from slaughterhouses will be essential for managing solid waste. Additionally, porcine and bovine gelatin products are prohibited or have limited permission in Jewish and Muslim areas, whereas poultry (chicken), fish, frog, and insect-origin gelatins can be used without complications worldwide. Poultry gelatin is preferable to fish gelatin due to its lack of unpleasant odor.[6]

The production of gelatin from CDRs is a relatively unexplored area, with only a few studies conducted. Consequently, our research is pioneering in this field. Before delving deeper, it is essential to define what CDRs are. CDRs are chicken parts obtained from chicken waste through mechanical deboning operations. During this process, pressure is applied to separate the chicken meat from a slurry of ground meat and bones in a mechanical deboner. The resulting waste material, CDRs, contains a high percentage of bone, skin, and connective tissues, with its composition depending mainly on the raw input material. Typically, CDRs consist of about 20% protein, of which approximately 30 – 40% is collagen.[7]

Collagen, the most abundant structural protein in animals and humans, constitutes about 30% of the total protein content. It is primarily found in connective tissues, providing strength and flexibility. Although collagen is indigestible by humans, gelatin, produced through the partial hydrolysis of collagen, is a digestible, water-soluble, odorless, and transparent polypeptide with a high molecular weight. The properties of gelatin are significantly influenced by factors such as the raw material, the age of the animal, the type of collagen, the processing method, the tissue type, and the species involved. However, gelatin consists of various collagen fractions and peptide chains, which differ in size and weight. These variations contribute to gelatin's low melting temperature below 35 °C.[8,9]

Gelatin is one of the most versatile biopolymers, and it is utilized across multiple industries due to its properties. In the cosmetic industry, it is a gelling agent in products such as bath salts, shampoos, sunscreens, body lotions, hair sprays, and facial creams. In the food industry, gelatin is used as a gelling, foaming, clarifying, and stabilizing agent in canned meats, wine and beer brewing, and confectionery items like fruit salads, ice cream, foam, and cottage cheese. Its film-forming capability allows it to be used as a coating material or edible film to extend the shelf life of products. They enhance the quality of tropical fruits, berries, and vegetables by reducing weight loss, preventing color changes, slowing respiration rates, controlling ethylene production, and delaying ripening. This approach has gained significant attention recently, driven by the growing interest in healthier food options and dietary habits. In the medical and pharmaceutical sectors, gelatin is employed in soft and hard capsule shells, hydrogels, nano microsphere containers, nanofibers, absorbable sponges, pharmaceutical additives, matrices for intravenous infusions, injection drug delivery microspheres, implants, and cell transplantation carriers. Emerging medical applications include using ink for 3D/4D printing, tissue engineering, and gelatin-based 3D scaffolds. In the photographic industry, gelatin is an adhesive additive to silver salts. In forensic science, gelatin is applied as a gelatin-lifter for shoe print lifting, fabric imprints, and fingerprints.[10,11]

The processing of collagen comprises a sequence of technological steps like chemical, thermal, physical, and mechanical techniques. These various treatments affect the properties of the nascent collagen, such as its solubility, physical stability, DNA content, and colony-forming units. The chemical extraction of gelatin through partial acid-controlled hydrolysis of collagen is known as type A gelatin, while partial alkaline-controlled hydrolysis produces type B gelatin. Traditional acid and alkaline hydrolysis methods are slow, costly, energy- and water-intensive, and significantly impact the environment.[6,12]

In contrast to chemical agents such as alkalis and acids, enzymes are more environmentally friendly because they are biodegradable and do not produce unwanted by-products. Additionally, they are cost-effective by reducing production expenses and helping achieve the desired functional properties of gelatin. During enzymatic protein hydrolysis, proteins are broken down into soluble forms through the catalytic action of proteases. Commonly used enzymes include industrially produced microbial enzymes, animal enzymes like trypsin and pepsin, and plant enzymes such as papain.[6]

Aims of the study

Our research team has been focusing on minimizing the volume of inedible ABPs in the food industry by exploring the potential of a lesser-studied ABP—the CDRs, as an alternative secondary raw material for gelatin production.

The first goal of this paper was to prepare gelatins from CDRs using biotechnological methods. Secondly, to test the gelling and surface properties of prepared gelatins. These most critical physicochemical properties are the gel strength (GS), yield (Y), dynamic viscosity (DV), ash content (AC), gelling point (GP), melting point (MP), water-holding capacity (WHC), fat-binding capacity (FBC), foaming capacity (FC), foaming stability (FS), emulsifying capacity (EC), and emulsifying stability (ES). Gelatin yield was also determined, as it is a key factor in calculating the overall financial viability of gelatin production.[13] Further, high Bloom-value gelatin was tested for the preparation of jellies. Finally, low Bloom-value gelatin film preparation and testing of their sorption characteristics were conducted.

Methodology

The raw material underwent analysis to determine its moisture, ash, protein, and lipid content. Moisture and ash levels were measured gravimetrically[14], with ash content specifically assessed after sample incineration[15]. Lipid content was quantified using Soxhlet extraction[16], while nitrogen content was evaluated using the Kjeldahl method[17].

Our study utilized an innovative biotechnological approach that involved conditioning collagen with a microbial endoproteinase (Protamex®) at 0.4% addition (based on the dry collagen weight) in the case of jelly production and at 0.5% addition in the case of edible film preparation. Protamex® is a versatile, cost-effective *Bacillus*-based protease that efficiently breaks down collagen under milder conditions (pH 5.5 – 7.5, low temperature) without excessive degradation while minimizing short-chain peptide formation and meets JECFA and FCC food-grade standards. The enzyme conditioning was followed by a three-step hot-water extraction to control collagen's chemical and thermal denaturation for gelatin preparation. The three-step extraction is preferred to obtain a higher yield of gelatin.[13,18]

In the case of CDR gelatin aimed to prepare jelly, the experiments were designed using the Taguchi method with two factors at three levels: factor A represented extraction time (20, 40, and 60 minutes) at the 2nd fraction, and factor B represented extraction temperature (60 ± 0.2 °C, 64 ± 0.2 °C, and 68 ± 0.2 °C) at the 2nd fraction. The 1st fraction was extracted at 56 ± 0.2 °C for 2 minutes and then 85 ± 0.3 °C for 7 minutes, while the 3rd fraction was extracted at 80 ± 0.3 °C for 60 minutes. The tenth experiment was a control, conducted without enzymes.[13]

Gelatin's properties were analyzed using methods including gel strength measurement at 6.67% concentration by depressing the solution by 4 mm, dynamic viscosity calculation at 60 °C ± 0.5 °C based on flow time, yield determination as a percentage of gelatin weight relative to defatted raw material, and additional tests for pH in a 1–2% solution and ash content through gravimetric analysis after burning the sample.[19] The prepared jellies were evaluated through sensory testing to compare their key characteristics with commercially available products. Thirteen lay assessors, aged between 26 and 65 and all from Central Europe, participated in the evaluation. They assessed the jellies on the following attributes: 1) appearance, 2) chewiness, 3) color, 4) aroma, 5) taste, and 6) overall acceptability. The sensory attributes were rated on a 7-point scale, where 1 indicated "I extremely like this product" and 7 indicated "I extremely dislike this product."

To prepare edible films from CDR gelatin, a three-step extraction process was employed with the following parameters: the first fraction was extracted at 60 ± 0.2 °C for 3 minutes, followed by 85 ± 0.3 °C for 7 minutes; the second fraction was extracted at 70 ± 0.3 °C for 60 minutes, then at 85 ± 0.3 °C for 7 minutes; and the third fraction at 80 ± 0.3 °C for 60 minutes.[18]

Gelatin films from each fraction were prepared using the solution casting method. The gelatin samples were dissolved in water to prepare a 14% concentration solution, poured into 70 × 125 mm^2 film-shaped molds, and dried in an oven at 35 ± 0.7 °C. The water content of the films was measured using Karl Fischer Titration. Water activity (a_w) was determined using an equilibrium moisture content equation (1), adapted for the Modified Halsey model to analyze gelatin films' sorption and desorption behaviors. These measurements were conducted at temperatures ranging from 20 to 40 °C and relative humidity (RH) levels from 40 to 75%, increasing in 10% RH steps, with an equilibration time of 240 minutes at each step. For desorption studies, the process was conducted in reverse. The gelatin films were placed on aluminum trays during the experiments to ensure no overlap between samples.

$$X_e = \left[\frac{\exp(a-bT)}{-\ln(a_w)}\right]^{\frac{1}{c}} \qquad (1)$$

Where X_e Is the equilibrium moisture content (%), aw is the water activity (decimal), T is the temperature (°C), and a, b, and c are coefficients that depend upon the product.[20]

Results and discussion

Parameters of gelatin preparation

The CDR raw material consists of 38.15% dry matter, with its composition based on dry matter including 28.59% ash, 25.97% lipid, 6.45% nitrogen, 40.31% total protein (calculated as nitrogen content × 6.25), and 68.3% collagen within the total protein content.

The main properties of gelatin that we tested and evaluated included Y on dry matter content, GS, DV, FC, FS, GP, MP, AC, WHC, FBC, EC, ES, and temperature interval of viscous state. Among these properties, GS is the primary attribute that most significantly indicates the quality of gelatin. The obtained results are presented in Table 1. Some parameters could not be measured due to the lack of a gelatin sample. The data were statistically processed and analyzed at a 95% significance level.[13]

Properties of gelatin jelly production

The obtained results identified two optimal conditions: the highest yield with a Bloom value suitable for the confectionery industry (260 Bloom) and the highest Bloom value gelatin fraction. The highest yield was achieved in the 9th experiment (68 °C extraction temperature and 60 minutes extraction time), where the Bloom value in the 2nd fraction was 289 Bloom, and in the 3rd fraction, it was 268 Bloom. The highest Bloom value was obtained in the 2nd fraction of the 8th experiment (68 °C extraction temperature and 40 minutes extraction time), with a value of 341 Bloom.[13]

Figure 1: The prepared gelatin gels, from left to right: 7th experiment third fraction, 5th experiment second fraction, 5th experiment third fraction, 7th experiment second fraction, 2nd experiment second fraction, 1st experiment third fraction, and 4th experiment second fraction.[13]

Table 1: Parameters of all 2nd and 3rd gelatin fractions in each experiment: gel strength (GS), yield (Y), dynamic viscosity (DV), water-holding capacity (WHC), fat-binding capacity (FBC), emulsification capacity (EC) and stability (ES), ash content (AC), foaming capacity (FC) and stability (FS), gelling point (GP), melting point (MP), and temperature interval of viscous state. Some parameters could not be measured due to the lack of a gelatin sample. The 1st fractions did not form a gel and were therefore not tested.[13]

Number of experiments	Number of extractions	GS [Bloom]	Y [%]	DV [mPa·s]	WHC [%]/ WHC [mL/g]	FBC [mL/g]	EC [%]	ES [%]	AC [%]	FC [%]	FS [%]	GP [°C]	MP [°C]	Temperature interval of viscous state [°C]
1. [60°C, 20 min]	2nd	208	2.54	3.2	–	6.9	43.3	96.2	–	–	–	15.6	35.2	19.6
	3rd	231	4.51	5.0	–	7.2	46.6	94.5	–	–	–	22.1	35.5	13.4
2. [60°C, 40 min]	2nd	241	3.67	3.6	–	7.7	48.1	98.1	–	54	12	18.9	35.0	16.1
	3rd	297	5.36	6.9	33.2/ 8.3	5.0	44.1	96.2	–	60	4	22.2	34.2	12.0
3. [60°C, 60 min]	2nd	334	9.02	4.5	38.4/ 9.6	4.6	44.1	100.0	0.01	36	2	19.9	37.8	17.9
	3rd	281	6.50	5.6	36.8/ 9.2	4.2	45.8	92.6	–	52	2	22.8	37.2	14.4
4. [64°C, 20 min]	2nd	217	3.10	3.9	-	5.4	45.6	100.0	–	–	–	21.8	36.4	14.6
	3rd	295	4.80	7.6	32.4/ 8.1	5.3	50	94.7	–	42	0	23.8	34.6	10.8
5. [64°C, 40 min]	2nd	256	5.36	4.1	37.2/ 9.3	5.6	44.8	100.0	–	32	0	19.9	37.0	17.1
	3rd	200	7.61	4.4	41.6/ 10.4	7.6	45.8	100.0	–	36	0	19.9	35.4	15.5
6. [64°C, 60 min]	2nd	278	7.05	4.9	37.6/ 9.4	7.8	45.8	100.0	–	50	4	21.8	35.3	13.5
	3rd	267	7.33	7.2	38.9/ 9.7	8.3	43.9	100.0	–	30	0	23.7	35.5	11.8
7. [68°C, 20 min]	2nd	271	5.64	4.4	37.7/ 9.3	8.8	47.5	96.4	–	42	0	19.3	37.5	18.2
	3rd	217	7.89	4.4	30.9/ 7.7	7.6	46.6	92.6	–	40	0	19.1	35.7	16.6
8. [68°C, 40 min]	2nd	341	5.36	4.5	39.3/ 9.8	9.5	45.6	96.2	–	44	4	20.9	32.3	11.4
	3rd	274	6.76	5.0	24.2/ 6.1	8.7	46.6	98.1	–	44	2	20.2	35.5	15.3
9. [68°C, 60 min]	2nd	289	11.56	3.4	34.3/ 8.6	8.1	44.8	96.2	0.004	42	4	18.0	34.4	16.4
	3rd	268	7.05	4.0	21.7/ 5.4	7.7	44.8	100.0	–	44	4	22.4	32.8	10.4
10. [64°C, 40 min]	2nd	304	5.07	4.2	36.0/ 9.0	6.2	46.6	96.3	–	46	2	20.6	35.5	14.9
	3rd	308	8.17	5.5	30.3/ 7.6	7.9	44.8	96.2	–	46	0	18.8	32.4	13.6

Parameters of gelatin jellies

The average results of each sample sensory results are shown in Table 2. Sample **A** was the jelly made from 260 Bloom porcine skin gelatin in a bottom-like shape; sample **B** was also from 260 Bloom porcine skin gelatin in a sea creature form; sample **C** was made from 289 Bloom CDR gelatin (9th experiment, 2nd fraction) in a bottom-like shape; and sample **D** was made from 268 Bloom CDR gelatin (9th experiment, 3rd fraction) in a bottom-like shape, shown in Figure 2.[13]

Table 2: The arithmetic average results of sensory testing of each sample at each criterion.[13]

Jelly	Appearance	Chewiness	Color	Smell	Taste	Overall acceptability
A	2.3	2.8	1.8	2.9	2.5	2.4
B	1.7	2.9	1.8	2.2	2.5	2.3
C	4.8	2.7	4.5	3.8	3.1	3.8
D	4.8	4.6	4.3	3.9	3.5	4.8

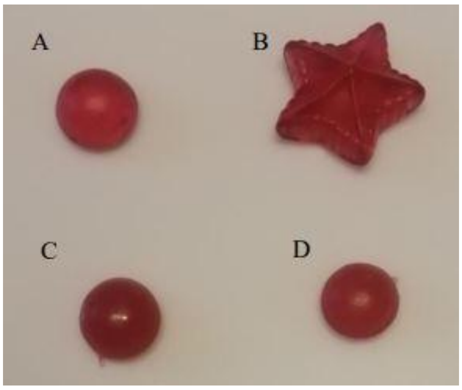

Figure 2: Samples: A) sample was the jelly from 260 Bloom porcine skin gelatin in a bottom-like shape; B) sample was also from 260 Bloom porcine skin gelatin in a sea creatures form; C) sample was made out of 289 Bloom CDR gelatin in a bottom-like shape; and D) sample was out of 268 Bloom CDR gelatin in a bottom-like shape.[13]

Parameters of gelatin film production

The parameters of the gelatin films are summarized in Table 2. The samples' initial water activity (aw) ranged from 0.38 to 0.40, with moisture content (measured at 103 °C for 4 – 5 hours) between 10 and 12%. The gel strength of the samples varied from 20.2 to 76.3 Bloom.[18]

Thickness is a critical characteristic of edible films, as it significantly influences coated food products' biological properties and shelf life. The thickness for edible films must be under ≤0.30 mm.[21] The water content in food influences its stability, appearance, texture, and taste and plays a critical role in controlling microbial growth. Edible films with low water content are more effective in minimizing damage and extending the shelf life of food products.

Table 3: The properties of each type of edible film.

Parameters	Fraction 1	Fraction 2	Fraction 3
Weight (mg)	9.6 ± 0.3	9.2 ± 0.3	9.2 ± 0.3
Thickness (mm)	0.28 ± 0.03	0.27 ± 0.02	0.30 ± 0.04
Area (mm^2)	33 ± 3	32 ± 4	31 ± 3
Water content (%)	10.0 ± 0.02	12.0 ± 0.03	11.0 ± 0.02
Gel strength (Bloom)	20.2 ± 0.5	76.3 ± 1.0	50± 0.8
Dynamic viscosity (mPa·s)	1.62 ± 0.03	1.96 ± 0.03	2.33 ± 0.04
Melting point (°C)	29.1 ± 0.5	33.2 ± 0.6	29.8 ± 0.05
Gelling point (°C)	15.6 ± 0.3	15.2 ± 0.3	13.3 ± 0.4
Water activity (decimal)	0.38	0.40	0.40

Tables 4 and 5 show that the moisture content of the samples never exceeded 23% of the equilibrium moisture content, which is considered an acceptable level of water content for edible films.[22] Thus, according to the statistical results, the Modified Halsey model was used to represent the results due to the high protein content of the gelatin samples.[20,23]

Table 4: The kinetic parameters for moisture adsorption of chicken gelatin from 75 to 40% of RH. Equilibrium moisture content: equilibrium moisture content at 75% RH; k: rate constant; Half-time: time to adsorb half of the total moisture content; Span: the difference between the initial and final moisture content of the sample (at 40 and 75% RH).

	Moisture adsorption	Fraction 1	Fraction 2	Fraction 3
20°C	Equilibrium moisture content (%)	19.90 ± 0.03	20.36 ± 0.06	19.9 ± 0.1
	k (min^{-1})	0.0109 ± 0.0002	0.006 ± 0.0001	0.0037 ± 0.0002
	Half-time (min)	63.6	115.5	187.3
	Span	7.5	7.8	7.2
30°C	Equilibrium moisture content (%)	20.54 ± 0.05	22.0 ± 0.1	20.7 ± 0.1
	k (min^{-1})	0.0186 ± 0.0005	0.0142 ± 0.0006	0.01 ± 0.0005
	Half-time (min)	37.3	48.8	69.3
	Span	8.3	9.9	8.6
40°C	Equilibrium moisture content (%)	21.4 ± 0.1	22.67 ± 0.06	21.85 ± 0.06
	k (min^{-1})	0.047 ± 0.003	0.039 ± 0.001	0.045 ± 0.002
	Half-time (min)	14.8	17.8	15.4
	Span	9.6	10.9	10.2

Table 5: The kinetic parameters for moisture desorption of chicken gelatin from 75 to 40% of RH. Equilibrium moisture content: equilibrium moisture content at 75% RH; k: rate constant; Half-time: time to adsorb half of the total moisture content; Span: the difference between the initial and final moisture content of the sample (at 40 and 75% RH).

	Moisture desorption	Fraction 1	Fraction 2	Fraction 3
20°C	Equilibrium moisture content (%)	16.25 ± 0.06	16.18 ± 0.09	15.98 ± 0.07
	k (min^{-1})	0.071 ± 0.004	0.065 ± 0.004	0.061 ± 0.003
	Half-time (min)	9.8	10.7	11.4
	Span	3.8	4.3	3.8
30°C	Equilibrium moisture content (%)	14.57 ± 0.06	14.7 ± 0.1	14.3 ± 0.1
	k (min^{-1})	0.092 ± 0.005	0.086 ± 0.005	0.06 ± 0.004
	Half-time (min)	7.5	8.1	11.6
	Span	5.8	7.1	6.0
40°C	Equilibrium moisture content (%)	13.21 ± 0.09	13.3 ± 0.1	12.9 ± 0.1
	k (min^{-1})	0.115 ± 0.005	0.10 ± 0.005	0.103 ± 0.005
	Half-time (min)	6.0	6.9	6.7
	Span	8.1	9.1	8.8

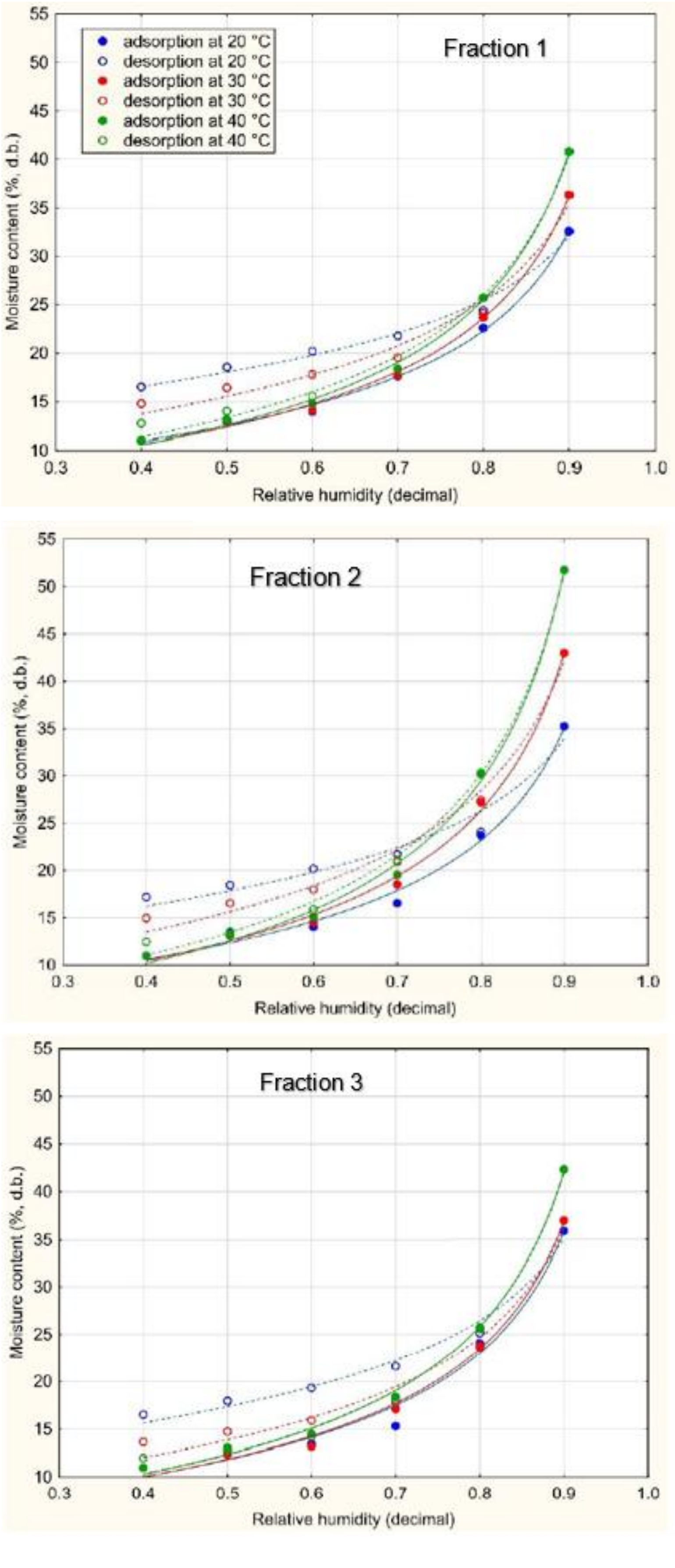

Figure 3: Sorption properties of each fraction at each temperature between 0.4 and 0.9 RH.

The adsorption and desorption behaviors of the samples were significantly influenced by temperature. Adsorption rate constants (k) increased with temperature for all samples, and the Span parameter indicated more significant moisture adsorption at higher temperatures. At 20 °C, Fraction 1 exhibited the fastest adsorption rate, followed by Fractions 2 and 3. This trend was also observed at 30 °C, but at 40 °C, the rate constants became similar across all samples. Moisture desorption was faster than adsorption for all samples and at all temperatures, with desorption rates generally increasing with temperature. However, for Fraction 3, the desorption rate remained constant at 20 °C and 30 °C and increased only at 40 °C. Differences in desorption rates between samples were minimal at a given temperature.

At higher relative humidity (RH) values (0.8 – 0.9), Fraction 2 adsorbed significantly more moisture at 30 °C and 40 °C than the other samples. In contrast, adsorption rates were similar across samples at RH levels of 0.4–0.7, with isotherm crossovers occurring at higher RH, where adsorption increased with temperature (shown in Figure 3 A), B), and C)). Fractions 1 and 2 showed consistent isotherm behavior across all temperatures, while Fraction 3 demonstrated a unique rebound in adsorption at 40 °C.

Sorption hysteresis, characterized by incomplete moisture desorption, was observed across all samples. The hysteresis effect decreased with increasing temperature and was almost negligible at 40 °C. This behavior is likely due to temperature-induced plasticity in the material, reducing the formation of microstructural gaps that trap water molecules during adsorption. Aguirre-Álvarez et al. also found the same phenomena in the case of bovine gelatin (gel strength 225 Bloom), pig skin gelatin (gel strength 270 Bloom), fish gelatin (gel strength 260 Bloom), and poultry gelatin (gel strength 240 Bloom) and Fikry et al. in case of whitefish skin gelatin at 25 °C, 35 °C, and even at 45 °C.[24,25]

Conclusion

Our study underscores the promising potential of CDRs as an alternative raw material for gelatin production, offering comparable properties to conventional gelatin. Using biotechnological methods, we successfully produced gelatins with desirable physicochemical properties suitable for various applications. Optimal extraction conditions led to high-quality gelatin, with a gel strength of up to 341 Bloom, demonstrating the viability of CDRs in various industries as pharmaceuticals (for nano- and microsphere containers and hydrogels), medicine (as an encapsulating material for drugs or chemicals), and food (for jellies, gelatin desserts, and meat emulsions). Sensory testing on jellies confirmed its potential in the food industry. However, a higher Bloom value (>260) is needed for texture comparable to candies produced with the use of commercial (pig or bovine) gelatins. A higher enzyme concentration revealed that slight changes in protease dosage significantly impact collagen structure, yielding lower molecular weight gelatin with reduced gel strength and viscosity, which is suitable e.g., for edible film production. Low-Bloom CDR gelatin films showed temperature- and humidity-dependent behavior, with enhanced plasticity and reduced sorption hysteresis at higher temperatures. Utilizing even the lower-Bloom value gelatins contributes to a circular economy, reducing inedible ABPs and providing a sustainable, financially viable alternative to traditional gelatin sources. Our findings suggest that CDRs could play a significant role in gelatin substitution, offering a more sustainable approach to gelatin manufacturing and reducing its environmental footprint.

Acknowledgment

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Využití zbytků po odstraňování masa z kuřat: Extrakce želatiny a její aplikace pro želé a fólie

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Souhrn

V posledních desetiletích došlo k významnému nárůstu odpadů v celém potravinářském sektoru. Odpad z potravin se rozděluje na odpad pro lidskou spotřebu a na nepoživatelné průmyslové vedlejší produkty, včetně nevyužitých živočišných tkání. Cílem této studie je snížit vedlejší živočišné produkty opětovným využitím kuřecího odpadu na extrakci želatiny. Proces extrakce želatiny ze zbytků po výrobě strojně odděleného kuřecího masa byl optimalizován použitím potravinářského enzymu; byly analyzovány fyzikálně-chemické a reologické vlastnosti získaných želatin. Teplota a doba extrakce byly zkoumány jako nezávislé faktory Taguchiho experimentálním schématem. Za optimálních podmínek získané želatiny vykazovaly vysokou pevnost gelu (196 – 353 Bloom) a viskozitu (3,2 – 7,6 mPa·s), což je činí vhodnými pro použití jako gelačních činidel, např. při výrobě želatinových cukrovinek. Želatiny s nízkou pevností gelu byly použity k přípravě jedlých filmů, přičemž testy jejich sorpčního a desorpčního chování odhalily teplotně a vlhkostně závislé vlastnosti; při vyšších teplotách došlo ke zlepšení plasticity a snížení sorpční hystereze. Environmentálně šetrná technologie zpracování zbytků po výrobě strojně odděleného kuřecího masa na želatiny je v souladu s principy oběhového hospodářství s minimalizací nevyužitých produktů vzniklých v průběhu technologického zpracování.

***Klíčová slova**: vedlejší produkty živočišného původu, želatina, želírovací vlastnosti, výtěžnost, povrchové vlastnosti, zbytek ze strojně odděleného kuřecího masa, vícestupňová extrakce, sorpční izotermy, filmy, želé.*

Impact of Grape Pomace Addition on the Mineral Profile of Long-Life Bakery Products

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Abstract

The incorporation of grape pomace into the preparation of innovative food products offers a promising strategy for the valorization of wine industry by-products. This study aimed to develop long-life pastry with the addition of grape pomace (Cabernet Franc) at levels of 5%, 10%, 15%, and 20%. The content of micro- and macroelements in the pastries was determined using an atomic absorption spectrophotometer. The concentration of potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na) were observed at concentrations 1692 – 3797 mg/kg, 323 – 5799 mg/kg, 89 – 132 mg/kg, and 317 –362 mg/kg DM, respectively. Among microelements, copper (Cu), zinc (Zn), manganese (Mn), iron (Fe), chromium (Cr), nickel (Ni), and cobalt (Co) were observed at concentrations of 0.63 – 1.07 mg/kg, 2.40 –2.66 mg/kg, 3.10 – 3.84 mg/kg, 14.05 – 19.30 mg/kg, 0.10 – 0.41 mg/kg, <LOD – 0.06 mg/kg, and <LOD –0.08 mg/kg DM, respectively. Lead (Pb) and cadmium (Cd) were detected in the ranges of <LOD – 0.08 mg/kg and <LOD – 0.70 mg/kg DM, respectively. Based on these findings, the addition of grape pomace at a 20% dose in durable bakery products demonstrates significant potential for the sustainable utilization of wine industry waste. It also contributes to enhanced levels of health-beneficial minerals in the final product, offering a valuable approach to producing nutritionally enriched food products.

Key words: *grape pomace; biscuits; minerals; heavy metals*

Introduction

A diet abundant in fruits and vegetables plays a crucial role in preventing diseases associated with oxidative stress. The risk of such diseases can be significantly mitigated by incorporating antioxidant compounds, such as polyphenols, vitamins, and minerals, into the diet[1].

Grape pomace, a by-product of winemaking and an excellent source of health-promoting bioactive compounds, offers a promising avenue for enhancing the nutritional value of innovative bakery products. Incorporating grape pomace into these products not only supports a healthier diet and reduces the prevalence of lifestyle-related diseases but also aligns with sustainability goals by repurposing waste and minimizing environmental impact. Grape pomace is a valuable source of nutrients, including carbohydrates, minerals, vitamins — particularly vitamin C — and both insoluble (cellulose, hemicellulose) and soluble (β-glucans, pectins, gums) dietary fiber[2]. Castellanos-Gallo et al.[3] report that grape pomace is also rich in dietary fiber and polyphenolic compounds, such as anthocyanins, flavanols, and stilbenes. Similarly, Echave et al.[4] highlight the presence of condensed tannins and resveratrol in grape pomace. These bioactive compounds are associated with a range of potential health benefits, including antioxidant, hypoglycemic, hypolipidemic, and anti-inflammatory activities, among others[5].

In addition to bioactive compounds, grape pomace is a rich source of essential minerals[6]. Caponio et al.[7] report that it contains a wide range of minerals, predominantly calcium, iron, zinc, potassium, and manganese. Similarly, Machado et al.[8] identify grape pomace as an excellent source of potassium, calcium, iron, manganese, and arachidic acid. Spinei and Oroian[9] also highlight that iron, potassium, calcium, and copper are among the primary minerals present in grape pomace. Minerals play a vital role in various biochemical processes within the human body. Potassium, for instance, contributes to protein and glycogen metabolism, regulates the body's water balance, lowers blood pressure, and reduces the risk of osteoporosis[10]. Calcium, another significant mineral in grape pomace, is essential for bone and tooth health, muscle contraction, and blood clotting[11].

The health-promoting properties of grape pomace make it a valuable ingredient for the development of functional foods, whose consumption may provide specific health benefits to consumers. Therefore, the aim of this study was to incorporate grape pomace into long-lasting bakery products and to evaluate the levels of macro- and micro-elements in the final products.

Experimental part

The grape pomace, consisting of skins, pulp, and seeds, used in this study was derived from the Cabernet Franc variety, sourced from the Slovak wine producer Tajna, s.r.o., whose vineyards are situated in the Nitra wine-growing region of Slovakia. The grape marc was dried at 50 °C for four days using a Memmert SF 110 dryer (Memmert GmbH, Schwabach, Germany) and subsequently homogenized for 60 seconds at 25,000 rpm with an IKA A10 batch mill to achieve a particle size of 0.7 mm (20 mesh).

Durable pastry (control sample) was prepared using wheat flour, sugar, butter, and vanilla. Variants of the pastry were then formulated by incorporating 5%, 10%, 15%, and 20% of the dried, homogenized grape pomace. Baking was conducted at 150°C for 20 minutes. After cooling, the biscuits were homogenized and prepared for subsequent analyses.

Figure 1: Biscuits with addition of grape pomace powder

Content of mineral elements was determined as described by Lidiková et al.[6]. A 1 g of sample was mineralized in 10 ml of concentrated HNO_3 and 5 ml of concentrated HClO using a MARS X-press mineralization device (CEM Corp., Matthews, NC, USA). The mineralized sample was filtered through quantitative filter paper (Filtrak 390, Munktell, GmbH, Bärenstein, Germany). For the determination of K, Ca, P, and Mg content, 2 ml of the filtered sample was diluted with distilled water to a final volume of 50 ml and analyzed against a blank solution using an atomic absorption spectrophotometer (VARIAN AASpectra DUO 240FS, Varian Ltd., Mulgrave, VIC, Australia).

To measure P content, 1 ml of the filtered sample was diluted with 8 ml of a reagent solution containing $C_6H_8O_6$, H_2SO_4, $(NH_4)_2MoO_4$, and $C_4H_4KO_7Sb{\cdot}5H_2O$, and deionized water was added to a final volume of 50 ml. The solution was analyzed against a blank using a UV/Visible Scanning Spectrophotometer (Shimadzu UV-1800, Shimadzu, Kyoto, Japan).

For the determination of Fe, Cu, Zn, Mn, Co, Cr, and Ni, a 1 g sample was mineralized in 5 ml of concentrated HNO_3 and 5 ml of redistilled water using the MARS X-press mineralization device. The mineralized sample was filtered (Filtrak 390) and diluted to 50 ml with distilled water. Elemental concentrations were analyzed against a blank using an atomic absorption spectrophotometer (Varian 240FS, Varian Inc., Mulgrave, VIC, Australia). The contents of Pb and Cd were determined using the Varian 240Z atomic absorption spectrophotometer.

Mercury was analyzed using cold-vapor atomic absorption spectroscopy with a selective Hg analyzer (AMA254, Al-tec, Prague, Czech Republic).

Statistical analysis was performed using XLSTAT software. To asses the normality of the data, Shapiro-Wilk test was performed. Based on the normality of the data, analysis of variance (ANOVA) with post hoc Tukey test, and Kruskal-Wallis test with post hoc Dunn test for was performed to determine the differences between samples. Spearman correlation was performed to assess relationships between individual mineral element contents. All analyses were performed in quadruplicate.

Results and discussion

The valorization of wine industry by-products, such as grape pomace, represents an effective strategy for recovering bioactive compounds and minerals while reducing the environmental impact of industrial waste. Due to its rich mineral profile, grape pomace can serve as a sustainable alternative source of both macro- and micronutrients, enabling the development of novel functional foods with potential health benefits for consumers[12]. Abouelenein et al.[13] reported that grape production by-products exhibit high concentrations of essential minerals, including calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na).

Table 1: Dry matter (%) and macro-element content (mg/kg) of biscuits with added grape pomace

Samples	**Dry matter (%)**	**K (mg/kg DM)**	**Na (mg/kg DM)**	**Ca (mg/kg DM)**	**Mg (mg/kg DM)**
Control	94.58±1.55	1692.8±88.5[a]	317.3±18.2[a]	325.3±22.5[a]	89.20±5.11[a]
5 %	94.06±1.98	2030.2±114.3[ab]	**345.4**±29.9**[bc]**	323.1±12.8[a]	89.20±6.63[a]
10%	94.35±0.38	2805.5±155.8[ab]	323.6±33.3[ab]	360.5±21.8[ab]	94.40±9.11[ab]
15%	94.50±1.02	**3792.5**±412.11**[b]**	**346.3**±29.8**[bc]**	457.1±33.5[ab]	113.9±7.54[ab]
20%	94.22±0.87	**3797.0**±285.4**[b]**	**362.6**±14.8**[c]**	**579.0**±39.5**[b]**	**132.8**±8.6**[b]**

Values marked with different letters are statistically significantly ($p < 0.05$) different; values marked with bold are statistically significantly ($p < 0.05$) higher than control

As shown in Table 1, the addition of 20% grape pomace to durable bakery products led to a statistically significant increase in calcium (Ca) content. Cormick et al.[14] have also highlighted the reutilization of wine by-products, particularly based on their Ca content. Calcium is a vital mineral required for several physiological functions, including blood coagulation, cell division, and muscle function.

When monitoring potassium (K) content, values ranged from 1692.8 to 3797.0 mg/kg, with the highest level observed following the incorporation of 20% grape pomace. Similarly, the magnesium (Mg) content reached its peak value (132.8 mg/kg) after the addition of 20% grape pomace. Magnesium is an essential nutrient that plays a critical role in energy production, muscle contraction, protein synthesis, bone growth, and blood pressure regulation[15].

Sodium (Na) content in the bakery products enriched with grape pomace ranged from 317.3 to 362.6 mg/kg. The higher levels of potassium compared to sodium promote mineral balance and contribute to the control of hypertension, as reported by Sousa et al.[16].

Incorporation of grape pomace into durable bakery products also led to an increase in the content of microelements (Cu, Zn, Mn, Fe, Cr, Ni and Co). The results are presented in Table 2.

Table 2: Micro-element content (mg/kg) of biscuits with added grape pomace

Samples	Cu (mg/kg DM)	Zn (mg/kg DM)	Mn (mg/kg DM)	Fe (mg/kg DM)	Cr (mg/kg DM)	Ni (mg/kg DM)	Co (mg/kg DM)	Pb (mg/kg DM)	Cd (mg/kg DM)
Control	0.63±0.03^{a}	2.40±0.03^{a}	3.10±0.19^{a}	15.45±1.11^{b}	0.10±0.01^{a}	<LOD^{a}	<LOD^{a}	<LOD^{a}	<LOD^{a}
5 %	0.89±0.05^{ab}	2.58±0.02^{ab}	3.28±0.31^{a}	16.13±0.98^{b}	0.27±0.02^{ab}	<LOD^{a}	<LOD^{a}	<LOD^{a}	<LOD^{a}
10%	0.91±0.08^{ab}	**2.66**±0.15^{b}	**3.68**±0.31^{b}	14.05±1.61^{a}	0.30±0.03^{abc}	<LOD^{a}	<LOD^{a}	<LOD^{a}	<LOD^{a}
15%	0.92±0.05^{ab}	**2.65**±0.21^{b}	**3.73**±0.25^{b}	**19.30**±1.11^{c}	**0.35**±0.21^{bc}	0.05±0.01^{ab}	**0.08**±0.05^{b}	**0.28**±0.05^{b}	0.20±0.01^{ab}
20%	**1.07**±0.09^{b}	**2.60**±0.15^{b}	**3.84**±0.28^{b}	**19.20**±0.78^{c}	**0.41**±0.21^{c}	**0.06**±0.01^{b}	0.07±0.03^{ab}	0.27±0.02^{ab}	**0.70**±0.09^{b}

Values marked with different letters are statistically significantly ($p < 0.05$) different; values marked with bold are statistically significantly ($p < 0.05$) higher than control; LOD – limit of detection

While certain minerals, such as potassium, calcium, and magnesium, showed clear increasing trends, others did not follow a uniform pattern. This highlights the complexity of mineral behavior in food matrices and suggests the need for further investigations into processing effects and interactions affecting mineral retention. The observed increase in trace elements in durable bakery products is a positive outcome, as the trace elements present in grape pomace have the potential to contribute to meeting daily intake requirements[17]. The incorporation of wine industry by-products into bakery products has been widely explored[4,18,19], though the focus has predominantly been on enhancing the phenolic compound content in the final innovative products.

In contrast, fewer studies have specifically addressed the impact of grape-derived products on the mineral content of biscuits. Our findings align with those of Theagarajan et al.[20] who reported that the 8% addition of grape pomace to biscuits increased mineral content from 1.71 to 3.04%. Similar observations were made by Poiana et al.[21] who stated that the 25% addition of grape pomace led to increases in the ash content of the products: from 1.84% (control) to a maximum of 2.29%. Giosuè et al.[22] documented elevated mineral levels in biscuits enriched with grape pomace (from 1.2% in control samples to 2.1 and 2.0% in samples with addition of 30 and 20% of grape pomace respectively). Likewise, Oprea et al.[23] reported a significant increase in K, Ca, Mg, Cu, Fe, and Zn content when flour enriched with grape pomace powder was incorporated into bakery products.

The addition of grape pomace may also influence the toxicological profile of the biscuits. Incorporating 15% and 20% grape pomace increased the lead (Pb) content to 0.28 and 0.27 mg/kg, respectively, while cadmium (Cd) levels rose to 0.27 and 0.70 mg/kg at these concentrations. However, when considering the average yearly consumption of biscuits and the tolerable weekly intake levels for Pb (1.750 mg/person/week) and Cd (0.175 mg/person/week), the consumption of such biscuits can be considered safe. Nonetheless, careful monitoring of the heavy metal content in grape pomace and its potential cumulative effects is essential to ensure long-term food safety.

Table 3: Correlations between contents of individual elements

	K	**Na**	**Ca**	**Mg**	**P**	**Cu**	**Zn**	**Mn**	**Fe**	**Cr**	**Ni**	**Co**	**Pb**	**Cd**	**Hg**
K	**1**														
Na	**0.62**	**1**													
Ca	**0.88**	**0.72**	**1**												
Mg	**0.89**	**0.76**	**1.00**	**1**											
P	**-0.61**	0.11	**-0.41**	-0.38	**1**										
Cu	**0.80**	**0.79**	**0.76**	**0.76**	-0.38	**1**									
Zn	**0.58**	**0.68**	0.38	**0.42**	-0.29	**0.72**	**1**								
Mn	**0.91**	**0.68**	**0.79**	**0.80**	**-0.63**	**0.87**	**0.82**	**1**							
Fe	**0.75**	**0.80**	**0.81**	**0.85**	0.02	**0.57**	0.36	**0.58**	**1**						
Cr	**0.89**	**0.72**	**0.79**	**0.79**	**-0.47**	**0.97**	**0.67**	**0.88**	**0.62**	**1**					
Ni	**0.90**	**0.66**	**0.94**	**0.95**	-0.34	**0.66**	0.30	**0.70**	**0.91**	**0.75**	**1**				
Co	**0.90**	**0.61**	**0.87**	**0.88**	-0.33	**0.60**	0.32	**0.68**	**0.92**	**0.72**	**0.98**	**1**			
Pb	**0.91**	**0.63**	**0.89**	**0.91**	-0.34	**0.62**	0.32	**0.69**	**0.92**	**0.73**	**0.99**	**1.00**	**1**		
Cd	**0.74**	**0.66**	**0.96**	**0.94**	-0.29	**0.70**	0.18	**0.63**	**0.74**	**0.70**	**0.88**	**0.76**	**0.80**	**1**	
Hg	**0.91**	**0.72**	**0.97**	**0.96**	**-0.51**	**0.88**	**0.50**	**0.87**	**0.72**	**0.89**	**0.88**	**0.80**	**0.83**	**0.92**	**1**

Values in bold are statistically significant ($p < 0.05$)

As showed in the Table 3, the correlation analysis revealed several strong relationships between mineral contents in long-life bakery products with grape pomace addition. A highly positive correlation was observed between potassium and magnesium ($r = 0.89$), calcium ($r = 0.88$), and manganese ($r = 0.91$), suggesting that grape pomace is a rich source of these elements and contributes significantly to their increased presence in the final product. Similarly, copper correlated strongly with chromium ($r = 0.97$), indicating similar distribution patterns within the matrix. Interestingly, phosphorus showed a weak and negative correlation with potassium ($r = -0.61$), calcium ($r = -0.41$), and magnesium ($r = -0.38$). This suggests potential interactions or competitive binding effects that may influence phosphorus retention in the bakery matrix. In terms of safety considerations, lead, cadmium, and mercury exhibited strong positive correlations with key minerals such as calcium ($r = 0.89$, $r = 0.96$, $r = 0.97$, respectively) and magnesium ($r = 0.91$, $r = 0.94$, $r = 0.96$, respectively). This indicates that while grape pomace enhances the nutritional profile, it may also introduce heavy metals that require careful monitoring to mitigate potential health risks.

These findings underscore the need for further investigation into mineral bioavailability and potential mitigation strategies for heavy metal accumulation in bakery products enriched with grape pomace.

Conclusion

This study demonstrated that incorporating grape pomace into long-life bakery products significantly enhances their mineral profile. Among the macroelements, potassium, calcium, and magnesium exhibited the most substantial increases, while microelements such as copper, zinc, and iron also improved. However, developing food products with unconventional ingredients requires balancing sensory appeal with nutritional benefits to meet consumer expectations. A key concern identified in this study is the observed increase in heavy metals, particularly lead and cadmium, after grape pomace addition. This finding highlights the need for careful selection, monitoring, and processing of grape pomace to ensure food safety. While moderate inclusion levels appear promising, for industrial applications, it is essential to investigate in more detail how to manage potential toxic effects associated with long-term consumption. Addressing these concerns is crucial to ensuring regulatory compliance and consumer safety.

For food producers, optimizing the level of grape pomace inclusion is critical to maximizing nutritional benefits while minimizing sensory and safety concerns. Future research should focus on improving the bioavailability of beneficial minerals, refining processing techniques to reduce heavy metal content, and conducting long-term risk assessments to support the safe and sustainable application of grape pomace in food products.

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Vplyv prídavku hroznových výliskov na minerálny profil trvanlivých pekárenských výrobkov

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Súhrn

Začlenenie hroznových výliskov do prípravy inovatívnych potravinárskych výrobkov ponúka sľubnú stratégiu zhodnocovania vedľajších produktov vinárskeho priemyslu. Cieľom tejto štúdie bolo vyvinúť trvanlivé pečivo s prídavkom hroznových výliskov (Cabernet Franc) v množstve 5 %, 10 %, 15 % a 20 %. Obsah mikro- a makroprvkov v pečive sa stanovil pomocou atómového absorpčného spektrofotometra (VARIAN AASpectra DUO 240FS/Z). Koncentrácia draslíka (K), vápnika (Ca), horčíka (Mg) a sodíka (Na) sa pohybovala od 1692 do 3797 mg/kg, 323 do 5799 mg/kg, 89 do 132 mg/kg a 317 do 362 mg/kg sušiny. Z mikroprvkov sa zistili koncentrácie medi (Cu), zinku (Zn), mangánu (Mn), železa (Fe), chrómu (Cr), niklu (Ni) a kobaltu (Co) v rozmedzí 0,63 – 1,07 mg/kg, 2,40 – 2,66 mg/kg, 3,10 – 3,84 mg/kg, 14,05 – 19,30 mg/kg, 0,10 – 0,41 mg/kg, <LD – 0,06 mg/kg a <LD – 0,08 mg/kg DM. Olovo (Pb) a kadmium (Cd) boli zistené v rozmedzí <LD-0,08 mg/kg a <LD-0,70 mg/kg sušiny. Na základe týchto zistení prídavok hroznových výliskov v 20% dávke do trvanlivého pečiva preukazuje významný potenciál pre udržateľné využitie odpadu z vinárskeho priemyslu. Prispieva tiež k zvýšenému obsahu zdraviu prospešných minerálnych látok v konečnom výrobku, čím ponúka cenný prístup k výrobe nutrične obohatených potravinárskych výrobkov.

***Kľúčové slová**: hroznové výlisky; sušienky; minerálne látky; ťažké kovy*

Utilizing Grape Pomace as a Functional Ingredient: A Case Study in Biscuit Production

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Abstract

The aim of the work was to prepare biscuits with 5, 10, 15 and 20% addition of grape pomace of the Merlot variety obtained from a Slovak wine company. For comparison, a control sample without the addition was also prepared. The amount of dry matter determined ranged in all samples at the level of ~ 94%; the total fat content slightly increased due to the addition, with the lowest value in the control sample (22.51%) and the highest in biscuits with 20% addition of pomace (24.07%). The total ash content ranged from 0.23% (control) to 0.71% (sample with 20 % addition of pomace). The crude protein content increased proportionally with the addition – the control sample showed a content of 5.97%, the sample with a 5% addition had a content of 6.17%, the sample with a 10% addition had a content of 6.29%, the sample with a 15% addition had a content of 6.35% and the sample with a 20% addition had the highest content - 6.41%. The addition of pomace caused an extension of the oxidative stability, which is a positive indicator in terms of the shelf life of the biscuits. The control sample showed a stability of 18.35 hours, while the sample with a 20% addition had up to 35.46 hours. Significantly higher amounts of mineral compounds were found in the biscuits with the addition, especially copper, zinc, manganese, magnesium and iron. The content of the hazardous elements cadmium and lead in the control sample and in the sample with the addition of 5 and 10% was not recorded. In the sample with the 15 and 20% addition, the amounts were found at the level of 0.6 and 0.8 mg/kg, respectively, but these values are in accordance with the legislation. From the sensory point of view, the biscuits were evaluated very well, and the 15% addition appeared to be the best.

Key words: *Merlot, ash, fat, crude protein, cereal products, sensory acceptance.*

Introduction

The main by-products of the wine industry include grape pomace, grape seeds, grape stems, yeast, and tartrate sediments. Grape pomace is the residual matter left after pressing fresh grapes, whether they undergo fermentation or not. It is one of the most significant by-products in the wine industry and consists primarily of the grape's weight, including the skins, seeds, and other solid components. This by-product is a complex material made up of 30% neutral polysaccharides, 20% pectic substances, 15% insoluble proanthocyanidins, as well as structural proteins and phenolic compounds.[1] Over the years, the utilization of grape pomace has been largely inefficient. In recent years, it is estimated that only around 3% of the grape pomace produced is repurposed for animal feed, while other uses include waste-based compost and potential applications in improving thermal insulation in building construction. Grape pomace is produced in large quantities during the short grape harvest period, resulting in a high concentration of by-products per unit of area.[2] Disposal methods like incineration or landfilling can be harmful to the environment due to the phenolic compounds in pomace, which lower its pH and increase its resistance to biological degradation. Other environmental concerns include pollution of surface and groundwater, unpleasant odors, the attraction of flies and pests that can spread diseases, and oxygen depletion in soil and groundwater caused by tannins and other compounds.

With the growing consumer demand for natural over synthetic products and increased focus on sustainable agricultural practices, there are a wide variety of potential applications for grape pomace. These include functional foods (rich in dietary fiber and polyphenols), food processing (biosurfactants), cosmetics (grape seed oil and antioxidants), as well as pharmaceuticals and dietary supplements (grape pomace powder). According to Dwyer et al.[3] the market potential for grape pomace in Canada suggests that if every gram of red pomace skin were sold, the potential profit could reach approximately 448 million euros. Additionally, if all grape seeds were used to produce oil, with each 750 mL bottle priced at 4.7 euros, the final profit could exceed 4 million euros. However, the market potential decreases when a significant portion of the grape pomace is used to create compost, which is then recycled back into the vineyard. Several food categories have successfully incorporated wine pomace products to enhance their phenolic content. Cereal products, particularly bread and cookies, represent the category with the highest number of applications, primarily using wine-pomace flours. Cookies made with seedless and wine pomace flours received higher acceptability ratings compared to those made with seed flour, while cereal bars were found to be an excellent option for incorporating grape seed flour. Other food products, such as marmalade, candies, salad dressings, and tomato puree, have also been fortified with wine-pomace ingredients. Additionally, a new functional seafood sausage was developed using meagre (*Argyrosomus regius*), and red skin extracts were incorporated into tea infusions at varying concentrations, ranging from 50% to 100%, to boost the phenolic profile and antioxidant activity of the infusions.[4]

Despite these advancements, a critical knowledge gap persists in understanding the full spectrum of grape pomace's applications and its impact on food quality and safety. While several studies have reported on the benefits of grape pomace in various food categories, comprehensive evaluations of its bioactive compounds and their synergistic effects in food matrices remain limited. Moreover, the economic viability of utilizing grape pomace across different sectors is not thoroughly explored, especially in the context of sustainable practices within the wine industry.

In Slovakian market missing products with grape pomace addition, so the main aim of this study was to prepare model biscuits with 5, 10, 15 and 20% grape pomace incorporation and subsequently determined nutritional and sensory quality of these biscuits.

Material and Methods

Grape pomace from Merlot variety was obtained from private Slovakian wine company from area Tajná (174 m.a.s.l.). Fresh pomace was dried in oven (Binder ED 56, Germany) 5 hours using temperature 50 °C. Dry pomace was homogenized (IKA RCP-24, Germany) for final particle size 0.1 mm.

The biscuits were prepared in accordance with an old family recipe provided by one of the authors (Ivanišová). The ingredients were purchased from local market and included white wheat flour, 00 extra, beet sugar, butter, and vanilla. Each type of biscuits was made and baked separately. Altogether five variants of biscuits were prepared: control sample, samples with 5%, 10%, 15% and 20%. After kneading, the dough was allowed to rest for 60 min at +4 °C. The dough was rolled with a roller to obtain a thickness about 6 – 7 mm. The desired shapes of biscuits were cut out of the dough and formed by hand. The biscuits were baked at 150 °C for 20 minutes in oven (Miwe condo, Germany). After cooling for 30 min, the biscuits were packed in polyethylene zipper resealable food bags and stored at +21 °C and 50% relative humidity prior to the analyses of their nutritional and sensory characteristics.

All the chemicals used were of analytical grade and were purchased from Sigma-Aldrich (St. Louis, MO, USA) and CentralChem (Bratislava, Slovak republic).

Dry matter, ash and protein were determined following the standard AACC method 08 – 01.[5] Nitrogen content was measured by the semi micro-Kjeldahl method. Nitrogen was converted to protein using the conventional factor of 5.7.

Fat content was determined with Ancom XT15 Fat Extractor (USA) in line with producer instructions – the sample (1.5 g, W1) was weighted to special filter bag (XT4, Ancom, USA) and dried for 3 hours in an oven (WTB, Binder, Germany) at 105 °C to remove moisture prior to the extraction. Samples were placed in a desiccant pouch for 15 minutes, re-weighted (W2) afterwards, and extracted for 60 minutes at 90 °C with petroleum ether. After the process, the samples were removed, dried in an oven at 105 °C for 30 minutes, placed in a desiccant pouch and re-weighted (W3). Fat content (%) was calculated using the following formula: [(W2-W3)/W1] x100.

The oxidative stability was determined in 892 Rancimat apparatus from Metrohm (Switzerland) according to ISO 6886:1997[6] utilizing a sample of 0.5±0.01 g. All samples were studied in temperature 120 °C, under a constant air flow (20 L/h). The induction times were printed automatically by apparatus software with the accuracy of 0.005.

The analysis of mineral compounds was performed with Varian model AA 240 FS equipped with a D2 lamp background correction system using an air-acetylene flame (air 13.5 L/min., acetylene 2.0 L/min, Varian, Ltd., Mulgrave, Australia). The results were compared with multielemental standard for GF AAS (CertiPUR®, Merck, Germany). A 1 g of sample was digested with mixture of HNO_3: redistilled water (1:1). Samples were digested in a closed vessel high-pressure microwave digester (MARS X-press, USA) for 55 min. After cooling to room temperature, the suspension was filtered through Munktell filter paper (grade 390.84 g/m^2, Germany) and diluted to 50 ml with distilled water. Then, the samples extracts were subsequently analysed for Cd, Pb, Cu, Zn, Co, Cr, Ni, Mn, and Fe. The wavelengths at which the heavy metals were analysed following the calibration process were as follows: Cd – 228.8 nm, Pb – 217.0 nm, Cu – 324.8 nm, Zn – 213.9 nm, Co – 240.7 nm, Cr – 357.9 nm, Ni – 232.0 nm, Mn – 279.5 nm, Fe – 241.8 nm.

The sensory properties of the prepared biscuits were determined by a taste panel consisting of 25 evaluators – certified trained panellists (in age from 25 to 65; 15 women and 10 men; STN EN ISO 8586:2023)[7]. The panellists were asked to evaluate general appearance, flavour, taste, overall acceptability, and aftertaste. A 9 – point hedonic scale was used to rate the samples, with scores ranging from 9 (like extremely) to 1 (dislike extremely) for each characteristic. The sensory evaluation was realized in professional sensory laboratory (AgroBioTech Research Centre, Slovak University of Agriculture in Nitra) with accordance to ISO 11132:2021[8].

All experiments were carried out in triplicate and the results reported are the results of those replicate determinations with standard deviations. The experimental data were subjected to analysis of variance (Duncan's test), at the confidence level of 0.05, using software SAS.[9]

Results and discussion

The results of dry matter content in the tested samples (Table 1) ranged from 93.30% (samples with a 10% addition) to 95.75% (samples with a 15% addition). All values were within the maximum limit for biscuits, which is 8–10%. Biscuits belong to long shelf-life products; under good storage conditions, such as in a dark, cold, and dry place, they can be stored for up to 6 months. In the study by Giosué et al.[8] the dry matter content in biscuits enriched with grape pomace was like that in our study, at 94%. The ash content (Table 1) was lowest in the control sample and increased linearly, with the highest value found in biscuits containing 20% grape pomace. In the study by Giosuée et al.[10] sweet biscuits with a 20% addition contained a higher level of ash compared to our study, at 2%. This may be attributed to the grape pomace, which varied in grape origin and recipe; they used soy milk as a different ingredient, which influenced the ash content. The crude protein content (Table 1) across all tested samples was comparable, with marginally increased levels noted at the 15% and 20% addition rates. These results align with those reported by Giosué et al.[10] who observed crude protein levels of 4.8% at the 20% addition rate and 5.8% at the 30% addition rate in sweet biscuits. In contrast, Troilo et al.[11] reported a protein content of 9% in muffins enriched with 15% grape pomace, which is higher than our findings. However, it is important to note that Troilo et al.[11] included milk in their recipe, which contributed to the elevated protein values. Indeed, grape pomace, which is the solid remains of grapes after juice extraction (including skins, seeds, and stems), has been identified as a valuable by-product in the food industry. According to Kumar and Kumar[12] its richness in essential amino acids like lysine and methionine makes it an attractive ingredient, particularly since these amino acids are often limiting in various plant-based and animal-based foods. By incorporating grape pomace, food products can potentially enhance their amino acid profiles, making them more nutritious without relying on traditional sources like soy, which is expensive and can trigger allergies in some individuals[13].

Table 1: Results of total dry matter, ash and crude protein in analyzed biscuits

Sample	Dry matter [%]	Ash [%]	Crude protein [%]
Control biscuit	94.43 ±0.11^{ab}	0.25 ±0.03^{e}	5.97 ±0.33^{b}
B 5 % addition	95.39 ±0.09^{a}	0.42 ±0.05^{d}	6.17 ±0.17^{b}
B 10 % addition	93.72 ±0.12^{c}	0.56 ±0.01^{c}	6.29 ±0.24^{a}
B 15 % addition	95.75 ±0.13^{a}	0.66 ±0.05^{ab}	6.35 ±0.12^{a}
B 20 % addition	93.96 ±0.07^{c}	0.71 ±0.02^{a}	6.41 ±0.09^{a}

B – biscuit; mean ±standard deviation; different letters in rows denote mean values that statistically differ one from another

The total fat content in the samples varied between 22.51% in the control samples and 24.07% in the samples with a 20% addition of grape pomace. This difference is not so statistically significant and can be attributed to the main fat source in the biscuits, which is derived from the butter used in the formulation. While grape pomace is generally known to contain between 5% and 10% fat, Pop et al.[14] reported values exceeding 20%. This variability in fat content highlights that the fat percentage in grape pomace can be greatly influenced by the specific variety used. The oxidative stability of fatty products is crucial, as highlighted in Table 2. Grape pomace has been shown to significantly enhance this stability. For instance, the control sample exhibited an induction time of only 18.35 hours. However, as the percentage of grape pomace added increased, there was a linear increase in oxidative stability, with the highest stability observed in samples containing 15% and 20% grape pomace. This improvement is largely attributed to the bioactive compounds present in the pomace, particularly those from the polyphenol family. According to Antonić et al.[15] many polyphenols remain in grape pomace following the processing of grapes due to incomplete extraction. The primary polyphenolic compounds found in this by-product include anthocyanins (which are present only in red grape pomace), catechins, flavonol glycosides, phenolic acids, and alcohols. Together with dietary fibers, these phenolic compounds are among the most valuable constituents of grape pomace, known for their health benefits, including the promotion of intestinal health and the prevention of chronic diseases and cancer. Numerous studies have demonstrated the strong antioxidant potential of polyphenols, making them effective agents for food preservation through the inhibition of lipid oxidation and their antibacterial properties. Enhancing oxidative stability is a critical technological parameter, and grape pomace can serve as a functional ingredient not only in biscuits but also in fatty animal products, which are particularly susceptible to oxidation.[16]

Table 2: Results of total fat content and oxidative stability in analyzed biscuits

Sample	Fat [%]	Oxidative stability [h]
Control biscuit	22.51 ±0.22^{b}	18.35 ±0.34^{d}
B 5 % addition	22.61 ±0.23^{b}	18.74 ±0.32^{d}
B 10 % addition	23.69 ±0.12^{a}	21.25 ±0.15^{c}
B 15 % addition	23.79 ±0.32^{a}	32.37 ±0.23^{b}
B 20 % addition	24.07 ±0.12^{a}	35.46 ±0.12^{a}

B – biscuit; mean ±standard deviation; h – hours; different letters in rows denote mean values that statistically differ one from another

Table 3: Mineral compound composition in analyzed biscuits

Sample	mg/kg								
	Cu	Zn	Mn	Fe	Cr	Ni	Co	Pb	Cd
Control biscuit	0.63 ±0.02[c]	2.40 ±0.12[b]	3.10 ±0.11[d]	15.45 ±0.22[c]	0.10 ±0.02[d]	ND	ND	ND	ND
B 5 % addition	0.89 ±0.01[ab]	2.58 ±0.11[a]	3.28 ±0.09[c]	16.13 ±0.23[b]	0.27 ±0.01[c]	ND	ND	ND	ND
B 10 % addition	0.91 ±0.08[a]	2.61 ±0.09[a]	3.68 ±0.07[b]	17.05 ±1.22[b]	0.30 ±0.01[bc]	ND	ND	ND	ND
B 15 % addition	0.92 ±0.09[a]	2.65 ±0.08[a]	3.73 ±0.02[b]	19.30 ±0.76[a]	0.35 ±0.02[b]	0.05 ±0.01[a]	0.08 ±0.22[a]	0.28 ±0.05[a]	0.20 ±0.02b
B 20 % addition	1.07 ±0.02[a]	2.66 ±0.12[a]	3.84 ±0.02[a]	19.20 ±1.33[a]	0.41 ±0.03[a]	0.06 ±0.01[a]	0.07 ±0.22[a]	0.27 ±0.07[a]	0.70 ±0.04a

B – biscuit; mean ±standard deviation; ND – not detected; different letters in rows denote mean values that statistically differ one from another

The addition of grape pomace to biscuits significantly enhances their mineral content, particularly increasing levels of essential nutrients such as copper, manganese, iron, and chromium. The most prominent improvements in mineral content were observed at 15% and 20% inclusion rates of grape pomace. This is particularly beneficial for vegan consumers, who are often at risk of anaemia due to insufficient iron intake. Importantly, while these higher percentages also introduced trace amounts of nickel, cobalt, lead, and cadmium, all detected levels remained within the legal limits as stipulated by Slovak food regulations[17], underscoring the safety of consuming these enriched biscuits. Heavy metals like lead, mercury, arsenic, and cadmium are typically recognized as systemic toxicants, posing health risks both in acute and chronic scenarios. Consequently, food contamination with such harmful metals is a significant concern that necessitates regulatory oversight. Research by Antonić et al.[15] highlights the variability in essential mineral compounds found in grape pomace, with iron levels reported to range from 5 mg to over 5468 mg per 100 g, and zinc levels spanning from 2 mg to 2254 mg per 100 g. These minerals contribute not only to dietary nutrition but also play a vital role in enhancing antioxidant potential, which is beneficial for overall health. Additionally, grape pomace serves as an excellent source of potassium, with concentrations reaching up to 3157 mg per 100 g. Potassium is crucial for cardiovascular health, as it helps lower blood pressure and mitigates the risk of osteoporosis by reducing urinary calcium excretion. Thus, incorporating grape pomace into food products like biscuits may represent a strategic approach to improving dietary mineral intake while ensuring safety and regulatory compliance.[18]

The sample with 15% grape pomace addition received the best score compared to other samples containing grape pomace. When evaluating the aroma, the evaluators were asked to assign a score from a range of 1 to 9, where a maximum of 9 points indicated an excellent, balanced, and pleasant smell. The best aromas were found in the samples with 15% and 20% grape pomace. Regarding taste, the biscuits with 15% grape pomace were rated as the best, followed by the samples with 5% and 10%. The sample with 15% grape pomace also achieved the highest score for overall acceptability, receiving 8 points (Figure 1). Generally, the samples (Figure 2) containing grape pomace were considered acceptable, though some evaluators detected foreign tastes and aromas reminiscent of herbs or bitterness. Conversely, some evaluators appreciated the nice fruity smell and taste of the samples with grape pomace. Overall, it can be concluded that the biscuits, particularly those with 15% grape pomace, were evaluated very positively, indicating that Slovakian consumers accept grape pomace in innovative food products. In a study by Giosué et al.[10] biscuits with 20% and 30% grape pomace, as well as a control sample without any addition, were evaluated. The grape pomace biscuits were characterized by more pronounced winy and red fruit aromatic and olfactory notes, while the control sample displayed stronger oily notes. The control sample also exhibited a more pronounced biscuit flavor and sweetness, whereas the grape pomace biscuits were notable for their bitterness and acidity. In terms of mouthfeel sensations, the control sample was higher in greasiness, as well as crunchiness and friability; the 20% biscuit also shared these characteristics. The 30% sample was the chewiest, firm, and astringent, and was accompanied by a seedy texture, like the 20% biscuits. These authors confirmed that smaller particle sizes of grape pomace negatively affected the hardness and color in terms of lightness, as well as the homogeneity of the pores. Muffins with 15% grape pomace in a study by Triolo et al. [11] were also rated as very good, possessing a pleasant fruity taste and aroma. Acun and Gül[19] observed that adding more than 5 % red grape pomace to cookies led to an increase in hardness.

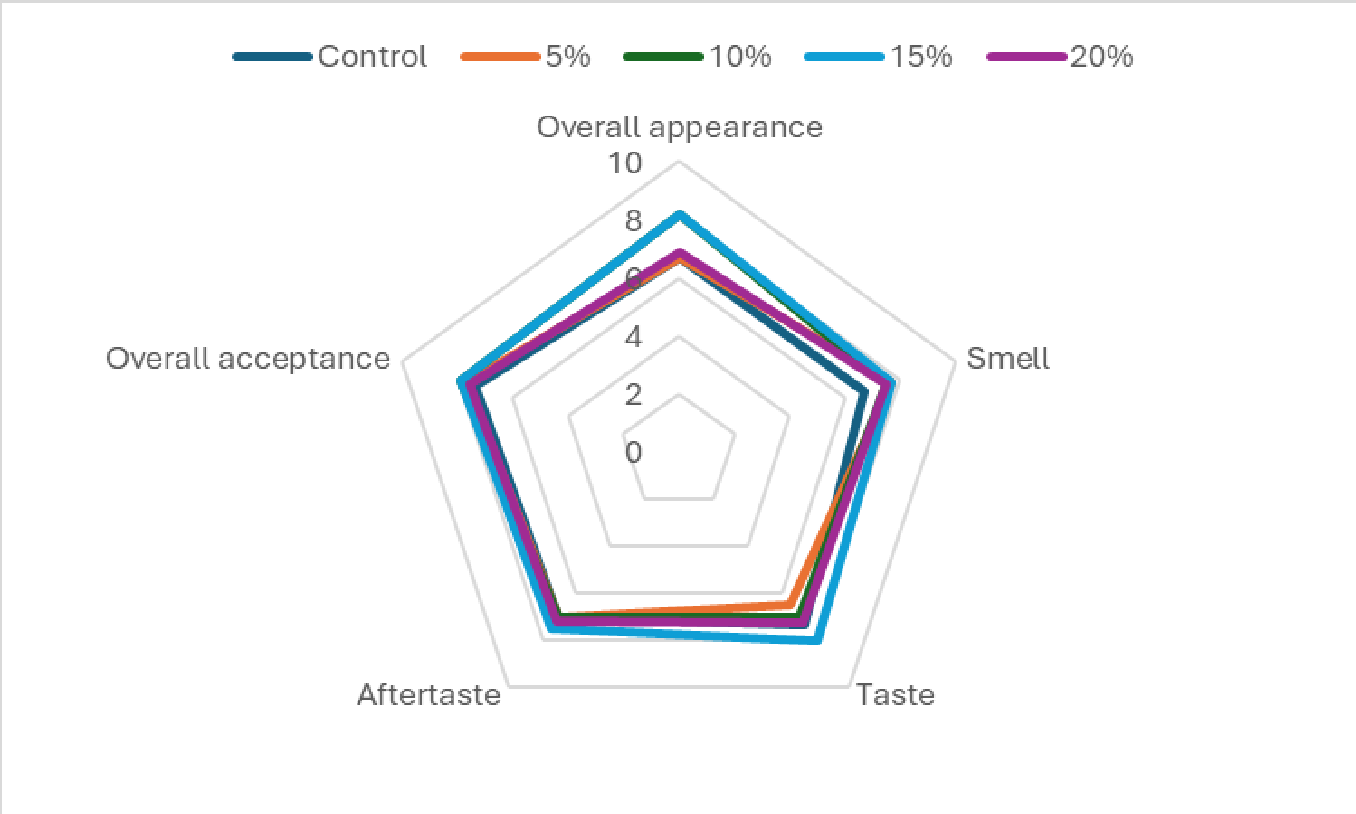

Figure 1: Sensory analysis of prepared biscuits (sum of all evaluators)

Figure 2: Biscuits with grape pomace (from left to right: control samples, sample with 5%, sample with 10%, sample with 15% and samples with 20%) (photo: Eva Ivanišová)

Conclusion

Grape pomace is a promising raw material for food enrichment, particularly in bakery products, which serve as suitable matrices for its incorporation. The benefits of using grape pomace extend beyond nutritional enhancement; it also offers technological advantages in terms of shelf life, as its biologically valuable substances can act as natural preservatives. Based on our results, we recommend incorporating grape pomace at levels of 15% in food applications, particularly in biscuit formulations. While our study evaluated additive levels up to 20%, preliminary findings suggest that these products may tolerate higher concentrations, potentially up to 30%. Although higher additions positively influenced nutritional parameters, sensory attributes remain crucial for consumer acceptance. Therefore, it is essential to note that exceeding 40% addition may negatively impact taste, particularly through increased bitterness, which could affect overall product acceptance. However, this study has some limitations that should be acknowledged. The sensory evaluation was conducted with a relatively small sample size, which may affect the generalizability of the findings. Additionally, the long-term effects of incorporating grape pomace on the shelf life and quality of baked goods require further investigation. Future research should explore consumer preferences in greater depth, as well as the impact of grape pomace on various types of baked products with differing formulations. Moreover, studies could investigate the sensory attributes and acceptability of formulations with higher pomace levels, alongside a broader assessment of the technological implications in different baking environments. This roadmap for subsequent studies will help to solidify the role of grape pomace in food enrichment and improve the understanding of its full potential in baked goods.

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Využitie hroznových výliskov ako funkčnej zložky: Prípadová štúdia při výrobe sušienok

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Abstrakt

Cieľom práce bolo pripraviť sušienky s 5, 10, 15 a 20% prídavkom hroznových výliskov odrody Merlot získaných od slovenskej vinárskej spoločnosti. Na porovnanie bola pripravená aj kontrolná vzorka bez prídavku. Stanovené množstvo sušiny sa vo všetkých vzorkách pohybovalo na úrovni ~ 94%; celkový obsah tuku sa pridaním výliskov mierne zvýšil, s najnižšou hodnotou v kontrolnej vzorke (22,51 %) a najvyššou v sušienkach s 20% prídavkom výliskov (24,07 %). Celkový obsah popolovín sa pohyboval od 0,23 % (kontrola) do 0,71 % (vzorka s 20% prídavkom výliskov). Obsah hrubého proteínu sa s prídavkom úmerne zvýšil – kontrolná vzorka vykazovala obsah 5,97 %, vzorka s prídavkom 5 % mala obsah 6,17 %, vzorka s prídavkom 10 % mala obsah 6,29 %, vzorka s prídavkom 15 % mala obsah 6,35 % a vzorka s prídavkom 20 % mala najvyšší obsah – 6,41 %.

Pridanie výliskov spôsobilo predĺženie oxidačnej stability, čo je pozitívny ukazovateľ z hľadiska trvanlivosti sušienok. Kontrolná vzorka vykazovala stabilitu 18,35 hodiny, zatiaľ čo vzorka s prídavkom 20 % mala až 35,46 hodiny. Výrazne vyššie množstvo minerálnych zlúčenín bolo nájdených v sušienkach s prídavkom výliskov, hlavne medi, zinku, mangánu, horčíka a železa. Obsah rizikových prvkov kadmia a olova v kontrolnej vzorke a vo vzorke s prídavkom 5 a 10 % nebol zaznamenaný. Vo vzorke s prídavkom 15 a 20 % boli zistené množstvá na úrovni 0,6 a 0,8 mg/kg, tieto hodnoty sú však v súlade s legislatívou. Po senzorickej stránke boli sušienky hodnotené veľmi dobre a ako najlepšie sa javil prídavok 15 %.

Kľúčové slová: *Merlot, popoloviny, tuk, dusíkaté látky, cereálne produkty, senzorická akceptácia.*

Consumer Motivations and Barriers to Food Waste Sorting: The Role of Segmentation in municipal communication

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Summary

Understanding the motivations and barriers consumers face in separating food waste is a prerequisite for effective communication between municipalities and citizens promoting waste sorting. The aim of this paper is to uncover the motivations and barriers across consumer segments, including the identification of segments that can be effectively targeted by municipalities. Using a survey instrument with 1,332 respondents, the study captured consumer attitudes and preferences, which were further complemented by data from a survey conducted among municipalities. A cluster analysis revealed four distinct consumer segments. For all segments, key motivations include the assurance that waste will be properly used and the availability of an adequate number of collection bins. Communication with consumers should emphasize specific examples of waste utilization and address negative externalities that hinder waste collection. Perceptions of barriers to waste collection and sorting vary across consumer segments.

Keywords*: Food waste, consumer segments, motivations, barriers, municipal perceptions, waste sorting behaviour.*

Introduction

Food waste (FW) has been shown to have a significant environmental impact[1], with associated negative environmental consequences[2]. Nevertheless, from a circular economy perspective, it can be regarded as a resource. For instance, it can be utilised to generate low-pollution energy[3] or to restore nutrients to soil in a natural manner within agricultural contexts[4]. As posited by numerous scholars, food waste is generated throughout the food supply chain[5], with consumers' households playing a major role in this regard1. The majority of extant research indicates that the majority of wasted food comes from households[6, 7]. Some report that approximately half of the food thrown away across the food supply chain comes from households[5].

In order to effectively utilise FW from households as a resource in accordance with the principles of the circular economy, it is imperative to engage as many households as possible in the collection of FW. This prompted our efforts to fill the research gap in food waste recovery research and first determine the willingness of consumers, as well as municipalities that cover waste collection, to engage in a FW collection and sorting system, and then to determine what barriers to FW collection both parties face. The **objective** of the present paper is twofold: firstly, to identify consumer segments depending on their perceived motivation and barriers to participation in the collection and sorting of FW; and secondly, to present recommendations applicable to communication messages of motivational campaigns for FW sorting. It is vital that the FW collection and sorting system and its communication are set up in such a way that the system is acceptable to all waste management actors, both citizens and municipalities.

Literature review

Food waste is defined as uneaten food scraps that are destined for disposal, representing the final stage of the food life cycle[6, 8]. The primary effort should be to minimize avoidable food waste and non-avoidable food waste should be sorted and utilized[6, 9]. Examples of avoidable food waste include baked goods, fruits and vegetables, which account for approximately 50% of avoidable waste, and biological residues and scraps, which constitute non-avoidable waste[6, 10.] It is desirable to use the unavoidable FW, for applications such as energy or agricultural purposes. Furthermore, it is essential to address food waste through effective sorting for subsequent utilisation. Consumer motivation plays a pivotal role in fostering proper participation in these practices[3].

Four segments of consumers were identified according to their attitudes towards waste sorting and motivation: the frequent waste collection resisters (willing to sort only occasionally, not bio-waste), the sceptics (opponents, distrust in waste recovery), the sorting enthusiastic (positively motivated to sort all types of waste) and the bio-waste sorting resisters (willing to sort all types of waste except bio-waste)[11].

Motivation to sort food waste

In addressing the issue of food waste, a holistic approach is imperative, even within the context of motivating food waste sorting[7]. Consumer waste sorting behaviour is significantly influenced by habitual and motivational factors, including environmentally responsible behaviour[12]. Environmental concern is a primary intrinsic motivator for individuals to sort waste[13], and financial incentives in the form of cost savings from proper sorting can be utilised to motivate consumers to do so[14]. Conversely, intrinsic motivation or extrinsic incentives, such as government publicity, have also been demonstrated to positively influence waste sorting behaviour[15]. Furthermore, the perceived value of sorting, the adequacy of collection facilities, and social interaction have been identified as key factors that can enhance active participation in waste sorting[16].

In the context of food waste, a significant number of contemporary studies have been conducted that focus on the motivations of consumers to reduce food waste[5, 7, 17]. These studies have identified that social norms and personal beliefs play a crucial role in motivating consumers to minimise food waste[11]. The issue of food waste is regarded as ethically problematic for financial reasons, where FW has an impact on wasted money, and for environmental reasons, where it is seen as a burden on the environment[18]. It is acknowledged that environmental awareness is an effective motivator for reducing food waste and should be invoked when eliciting interest in food waste sorting[19]. The aforementioned motivators should also be tested for the possibility of motivating consumers to sort food waste, which is the focus of this paper.

Barriers to sort food waste

Consumers face several barriers to potentially sorting food waste. These include the inconvenience of collection, which includes the effort consumers have to put into sorting, and lack of information, where consumers are unsure how to sort correctly[20]. Lack of knowledge of correct sorting can be a major barrier to waste sorting[21]. Consumers need time to sort waste in addition to the effort involved, and the time required for collection can be an additional barrier[20, 22].

A further barrier to sorting is consumers' uncertainty about the subsequent environmental benefits of waste management, due to a lack of confidence in the recovery of waste[13]. In the sorting process itself, consumers are concerned about the hygiene aspects of sorting, due to the rapid spoilage of food, especially odour[23]. Another barrier to sorting food waste is financial. Consumers are reluctant to invest in the necessary equipment for food waste collection, such as buckets or degradable bags, which could be addressed by financial incentives and subsidies[24].

Communication of efficient sorting of food waste

Clear communication of collection and sorting instructions can be useful in overcoming consumer perceived barriers such as perceived time[22]. The role of policy makers7 is crucial in setting up the communication of how FW is sorted and collected[7, 25]. Residents should first be convinced of the seriousness of the local government's intention to implement this policy and then begin to see waste sorting as a civic duty[26]. Therefore, a simple approach to waste separation[9] should be developed for consumers and properly communicated so that consumers are well informed about the options. In fact, most consumers are motivated to reduce food waste, so simply showing them how to sort properly[27] is enough. Short distances to collection points are needed, as well as easy access to the right information, such as information stickers[28]. Consumer education is needed to provide information on the correct handling and sorting of FW[21, 29]. The utilisation of mass media has the potential to facilitate the communication of strategies aimed at the reduction and separation of food waste. It is imperative that these messages are adapted to suit the specific age groups and personal values of the audience[30]. The dissemination of information regarding food waste segregation should be conducted through the medium of public service announcements[25].

Data and methods

This study utilised a unique primary dataset, collected via a questionnaire survey among consumers in the Czech Republic during the period September to December 2022, employing the CAWI method. The target respondents were consumers living in housing estates without garden, where the greatest potential for involvement in central food waste collection is seen. A sample of 1,332 individuals was obtained by applying quota sampling with six quota characteristics (see Table 1). The structure of the sample and the baseline were validated against EU-SILC (EU-Statistics on Income and Living Conditions)[31] microeconomic data from 2022, which is representative of the population structure [31]. Disposable household income is expressed in monthly terms and converted from CZK to EUR at the average exchange rate in 2022.

Table 1: Identification of respondents

	Questionnaire, n = 1332, [%]	**EU-SILC [%]**
Gender		
Men	47.9	48.6
Women	52.1	51.4
Age group		
18-24 years	8.5	7.6
25-34 years	17.2	14.8
35-44 years	17.4	18.2
45-54 years	18.8	18.8
55-64 years	15.0	15.0
65 and more years	23.1	25.6
Economic activity status		
Employees	56.7	46.7
Self-employed	8.0	9.5
Retired	24.1	25.9
Unemployed	2.0	2.7
Inactive (students, maternity leave, other)	9.2	15.2
Highest education attained		
Primary	1.7	0.2
Secondary (lower)	12.5	12.0
Secondary (complete)	54.9	66.9
Tertiary (university)	30.9	20.9
Number of household members		
1	18.5	32.1
2	39.5	32.1
3	21.6	16.7
4	17.2	14.9
5 and more	3.2	4.2
Disposable household income		
Less than 30 000 CZK (1170 EUR)	24.5	35.4
30 001 to 45 000 CZK (1755 EUR)	30.3	22.6
45 001 to 60 000 CZK (2340 EUR)	24.4	18.1
60 001 to 75 000 CZK (2925 EUR)	12.2	11.1
More than 75 000 CZK	8.6	12.8

Source: own questionnaire survey, n = 1332; [31]

The application of cluster analysis with the K-means algorithm has been demonstrated to offer advanced capabilities for the identification of consumer segments based on their motivations and barriers to sorting food waste. The K-means algorithm has been selected for the identification of homogeneous groups within a large dataset. The K-means algorithm is an iterative procedure that minimises the function of

$$f_{KP} = \sum_{h=1}^{k} \sum_{i=1}^{n} u_{ih} \|x_i - \bar{x}_h\|^2 \ ,$$

where the $\mu_{ih} \in \{0,1\}$ elements indicate whether the i-th object belongs (value 1) or doesn't belong (value 0) to the h-th cluster and is a vector of average values of the h-th cluster[32]. The following conditions must be met:

$$\sum_{h=1}^{k} u_{ih} = 1 \ for \ i = 1, 2, \dots, n \quad and \quad \sum_{i=1}^{n} u_{ih} > 0 \ for \ h = 1, 2, \dots, k.$$

Following segmentation, the demographics of the respondents assigned to each cluster are quantified in order to identify each segment.

The findings, based on data from the consumer perspective, are supplemented by an analysis of data from the municipal perspective, which was obtained through a subsequent questionnaire survey targeting representatives of municipalities and districts where housing estates without gardens are located. The data collection was carried out in 2023 in the form of CAWI and a dataset of n = 59 was obtained, with 96.6% of the data relating to towns with a population size of 5-99 thousand inhabitants. The data are representative of all regions of the Czech Republic (Table 2).

Table 2: Distribution of respondents in the regions of the Czech Republic

	Absolute	**Relative**
Prague	6	10.2
Central Bohemian	7	11.9
South Bohemian	4	6.8
Plzeň	1	1.7
Karlovy Vary	2	3.4
Ústí nad Labem	4	6.8
Liberec	3	5.1
Hradec Králové	3	5.1
Pardubice	5	8.5
Vysočina	4	6.8
South Moravian	6	10.2
Olomouc	4	6.8
Zlín	3	5.1
Moravian-Silesian	7	11.9
Total	59	100.0

Source: own questionnaire survey, n = 59

The analysis of the research data was conducted using IBM SPSS Statistics 27 software.

Results and discussion

The current level of sorting of household food waste, which includes all food waste (both plant-based and animal-based components of food waste), is first compared with the sorting of other types of waste to which consumers are accustomed. The present study measured the current level of waste sorting by Czech consumers in a questionnaire survey. The scale of measurement used was a seven-point scale ranging from 1 (lowest) to 7 (highest) perceived level of sorting. The results of the survey revealed that consumers sort plastic, paper and glass the most, while food waste is sorted the least (see Table 3).

Table 3: Waste sorting rate of Czech consumers

	Plastic	**Paper**	**Glass**	**Food waste (plant-based and animal-based waste from kitchen)**
Average values on a scale of 1-7	6.06	5.83	5.84	3.12

Source: own questionnaire survey, n = 1332

In response to questions regarding the level of waste sorting in municipalities, municipal representatives provided consistent responses. According to the opinion of municipal representatives, the most established sorting is paper and plastic. Regarding the sorting of food waste, 22% of municipality representatives stated that this waste is sorted in their municipality. Most municipalities report that food waste can currently only be sorted at the level of plant residues into bio-waste.

Consumer willingness to separate food waste

The majority of respondents (86%) expressed a desire to sort food waste; however, 46% of them reported a lack of options regarding how and where to do so. A more detailed analysis of consumer willingness to sort FW (Fig. 1) revealed that one third of consumers (31%) already engage in partial sorting. A negligible percentage of consumers expressed a lack of interest or intention to sort FW. A mere 5% of respondents consider FW sorting to be of negligible importance, while 2% of respondents are reluctant to engage in FW sorting due to concerns regarding FW handling. A modest gender bias is observed (p-value 0.021; Contingency coefficient Phi = 0.106), indicating a marginally higher propensity among women to engage in FW sorting.

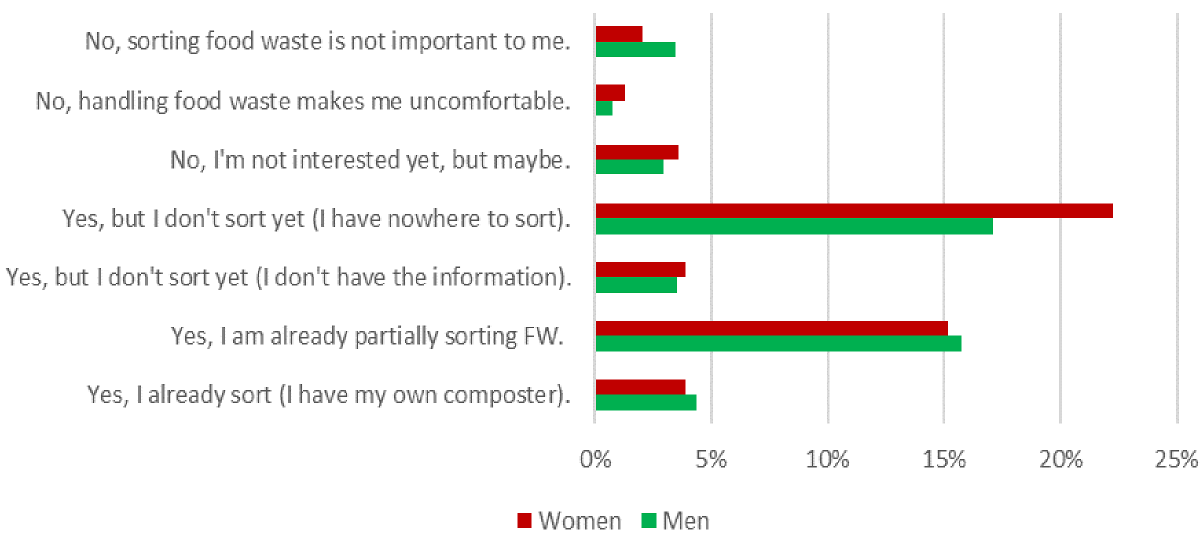

Figure 1: Willingness of consumers to sort FW
Source: own questionnaire survey (n = 1332)

95% of municipalities are willing to introduce a separate food waste system. For a potential food waste collection system to work, the preferences and expectations of municipalities and consumers themselves need to be aligned. Consumers who expressed a willingness to sort food waste (n = 1145) further specified their preferences on how to sort. Most of them are aware of the perishability of this type of waste and prefer to take out FW at frequent intervals (37% of them 1-2 times per week, 36% 3 or more times per week). Municipalities are inclined towards less frequent collection, half of them preferring an interval of 1 time per week. The preferred container for household food waste collection is some bag they find at home or the biodegradable bag, but households are not willing to pay for it (Figure 2).

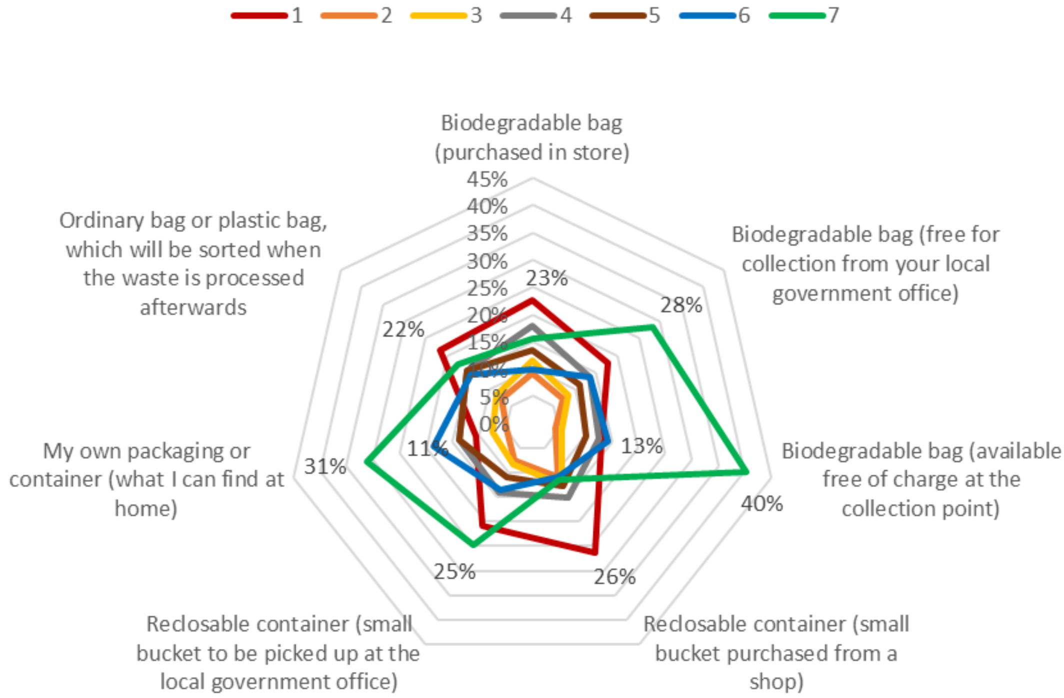

Figure 2: Preferred container for FW collection
Source: own questionnaire survey (n = 1332)

One of the key challenges in implementing a FW collection system is the financial burden, which municipalities are often reluctant to fully assume. In the present study, only a third of municipalities were willing to finance biodegradable bags, while 57% expressed willingness to provide resealable containers and again the preferred form of distribution at the municipal office or home delivery prevails. In terms of the food waste collection system, a small container or bucket seems to be a suitable option for food waste collection, where the waste is collected in the household and then taken to a larger collection container. The utilisation of biodegradable bags in food waste management faces challenges of contamination of food waste as well as the persistence of residues that could affect the desired properties of the waste[33].

To address these financial constraints, many European countries have introduced economic instruments such as the "Pay-As-You-Throw" (PAYT) system, which aligns with the "polluter pays" principle[34]. PAYT is designed to incentivize waste reduction by charging households based on the amount of non-recyclable waste they generate, encouraging greater participation in FW sorting[35, 36]. Different models exist, including volume-based pricing, weight-based schemes, or prepaid bag and tag systems, each tailored to local conditions[37]. In some European cities, PAYT has been integrated with digital tracking tools, such as smart waste bins or prepaid collection bags, ensuring both efficiency and fairness in waste management[38]. While the system has successfully reduced FW generation in countries like South Korea[39], its effectiveness depends on additional supportive measures, including clear communication strategies and public trust in waste processing infrastructure[40]. Given the financial concerns expressed by municipalities in this study, a well-designed PAYT scheme could provide a structured and equitable way to distribute costs, ensuring that FW collection remains accessible while maintaining public support for sorting initiatives.

Consumer segments by motivation and barriers to food waste collection

Segmentation criteria related to perceived motivations and barriers from the perspective of consumers entered the cluster analysis. These are their statements on the issue of motivation and barriers, rated using a scale of 1 (no motivation/barrier)-7 (high motivation/barrier). The resulting segmentation contains four segments that capture the variability in consumer data (Table 4). In the case of five or more segments, the differences between some segments become blurred. The most frequently perceived motivation is environmental improvement (M1) followed by motivation in waste treatment and recovery awareness (M2). This is in line with another study reporting that consumer perceived environmental value of sorting supports consumer intention to sort[41]. Other motivations include reducing fees for collecting mixed municipal waste (M4), ensuring sufficient bins/containers (M5) and ensuring a clean collection environment (M6). Segments 1 and 4 attach high importance to most motivators, with segment 4 also attaching importance to most barriers other than lack of time to sort. Segments 2 and 3 feel lower motivation, which will need to be supported by appropriate forms of communication. Segment 2 also shows importance for almost all barriers.

Table 4: Segmentation by motivation and barriers to food waste sorting

	Segment 1	Segment 2	Segment 3	Segment 4
M1: environmental improvement	6	5	5	6
M2: awareness of the subsequent treatment of waste	6	5	5	6
M3: social pressure of the environment – most sort	6	4	5	6
M4: reduction of fees for collection of MSW in smaller volumes	6	5	5	6
M5: sufficient number of containers	6	5	5	6
M6: clean environment at the collection point	6	5	5	6
M7: less frequent collection of MSW	4	3	3	3
M8: limiting the number or volume of MSW containers	4	3	2	3
M9: possibility of disposing of food in its original packaging	5	5	4	5
B1: odour	4	6	4	6
B2: insects	4	6	3	6
B3: rodents	3	5	4	6
B4: multiplication of harmful micro-organisms	3	5	3	6
B5: lack of containers	5	6	4	6
B6: lack of knowledge about the use of FW	4	5	4	5
B7: lack of time to sort waste	2	4	3	3

Source: own questionnaire survey (n = 1332)

The following table (Table 5) provides the segment identifiers. The last column contains the structure of the whole sample under study and the values with the most frequent categories within the segment are marked in bold. By comparing these values against the entire set, the specificity of the segment can be ascertained. In Table 5, above-average values are highlighted in bold, i.e., the above-average occurrence of a certain category of respondents in a segment.

As demonstrated in Table 5, the initial segment is distinguished by a higher-than-average proportion of younger age groups (18-44 years) and slightly elevated incomes in comparison to the whole population. Notably, there is a higher representation in the category of CZK 45,001 to 60,000. The analysis further reveals that two-person households are predominantly represented, though there is an above-average proportion of three- and four-person households in comparison to the entire sample. In the second segment, the middle-aged population is most often represented (above-average numbers of respondents aged 35 – 54) with an above-average representation of university-educated individuals. In terms of the number of household members, it includes a slightly below-average number of two-person households and, conversely, a slightly higher number of four-person households.

The third segment is characterized by a male preponderance and also an above-average incidence of self-employed individuals. In terms of other categories, it almost follows the structure of the total population. The fourth segment is mainly represented by women and an above-average representation of the 65 and more year's age category and economically active retirees. This segment exhibits a below-average income profile (Table 5).

Table 5: Identification of segments

	Segment 1	Segment 2	Segment 3	Segment 4	Total
Gender					
Men	48%	**52%**	**59%**	38%	48%
Women	52%	48%	41%	**62%**	52%
Age group					
18-24 years	**12%**	8%	10%	6%	9%
25-34 years	**21%**	16%	**22%**	13%	17%
35-44 years	**20%**	**22%**	18%	13%	17%
45-54 years	18%	21%	16%	19%	19%
55-64 years	11%	14%	13%	**19%**	15%
65 and more years	18%	19%	21%	**30%**	23%
Economic activity status					
Employees	**60%**	**61%**	55%	52%	57%
Self-employed	9%	7%	**10%**	7%	8%
Retired	21%	21%	22%	**32%**	24%
Unemployed	1%	2%	3%	2%	2%
Inactive and others	9%	9%	10%	7%	9%
Highest education attained					
Primary	1%	2%	3%	1%	2%
Secondary (lower)	11%	14%	11%	13%	13%
Secondary (complete)	**57%**	50%	54%	**58%**	55%
Tertiary (university)	31%	**34%**	32%	28%	31%
Number of household members					
1	16%	20%	16%	20%	19%
2	38%	36%	**41%**	**42%**	40%
3	23%	22%	23%	20%	22%
4	**20%**	**19%**	18%	14%	17%
5 and more	3%	3%	2%	4%	3%

Disposable household income					
Less than 30 000 CZK	21%	24%	22%	**28%**	25%
30 001 to 45 000 CZK	30%	29%	29%	**32%**	30%
45 001 to 60 000 CZK	**27%**	24%	**26%**	23%	24%
60 001 to 75 000 CZK	12%	13%	13%	11%	12%
More than 75 000 CZK	10%	10%	10%	6%	9%

Source: own questionnaire survey (n = 1332)

The followed identification of segments is based on the values that occur most frequently in Table 5. The creation of personas for each segment is then undertaken, with the aim of representing typical members of the segment (see Table 6). Each segment is also assigned a name according to the motivations and barriers that have been identified in Table 4.

There is a need to educate citizens on proper waste sorting. Table 6 also summarises the communication intentions that need to be communicated to the segments as part of the education campaign. The important role of educating consumers on the correct way to sort waste using appropriate communication channels is also underlined in other research[17, 21, 27].

Table 6: Design of personas for segments

	Segment 1	**Segment 2**	**Segment 3**	**Segment 4**
Segment Characteristics	Sorting inclined	Distrustful	Unafraid	Worried
Persona identification	Female, 38 years, employed, full secondary education, household with husband and 2 children, disposable income 48 thousand CZK	Male, 43 years, employed, university educated, household with wife and child, disposable income 73 thousand CZK	Male, 33 years, self-employed, secondary education, two-person household, disposable income 70 thousand CZK	Female, 69 years, retired, secondary education, two-person household, disposable income 28 thousand CZK. CZK
Communication intent	Inform about practical aspects of sorting (existing motivation sufficient, barriers proportionally low)	Mitigate barriers (especially insects and smells), encourage motivation with information (on waste utilisation, etc.)	Promote motivation by providing information (on waste recovery, impacts of sorting, etc.)	Provide information to mitigate barriers and remove concerns (especially odour, pests, number of containers, etc.)

Source: own elaboration based on results from Table 5

Another research interest is to identify the attitudes of public administration representatives. The primary motivation for municipalities is to reduce the amount of landfill waste in the vicinity of the municipality, which corresponds to consumer motivation regarding the improvement of the environment in the vicinity. In addition, citizen satisfaction and the use of food waste in a biogas plant would be motivating factors for municipalities.

Municipalities see the biggest barrier to FW collection as financial. At the same time, however, most municipal representatives said that the municipality would be willing to share the cost of collecting food waste to a composting plant. Furthermore, municipalities perceive the difficulty of ensuring a clean collection environment and are concerned about the poor sorting of waste by citizens.

The municipality has determined that the most efficacious means of disseminating information regarding the collection of messages is through the medium of the local newsletter, an article on the municipality's website, and simple social media posts. The majority of consumers in all segments would prefer to learn about the sorting process at the point of sorting, directly on the collection bin label (70% of consumers).

The subsequent most favoured method of information dissemination across all segments is the distribution of an information brochure in the mailbox (46% of consumers). In the fourth segment, there is an indication of the importance of the message in the local newsletter, while in the first segment there is a higher-than-average response for social media compared to the other segments. The detail of the preferred communication results (Figure 3) shows how many respondents in a given segment chose a particular option as their preferred form of communication.

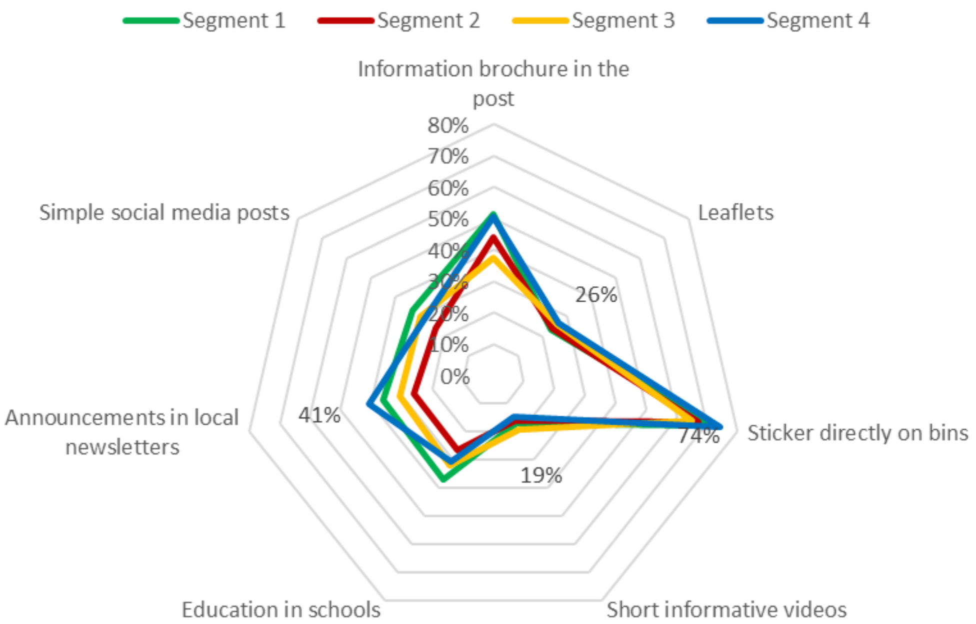

Figure 3: Preferred form of communication of information on waste sorting
Source: own processing of the questionnaire survey, n = 1332

Conclusions

Households are encouraged to consume and reduce waste responsibly. However, unavoidable waste, including unavoidable food waste (peelings, trimmings, etc.), is and will continue to be generated in households[6, 10]. In the Czech Republic, consumers have not yet adopted the practice of sorting food waste. However, a positive finding is the willingness of citizens and municipalities to sort food waste. This potential is not fulfilled in the Czech Republic, as half of the consumers willing to sort state that they do not have the means to sort FW.

In order to establish a successful functioning system for the collection of sorted food waste, it is necessary to identify the preferences of all waste management actors, starting with consumer preferences, as consumers need to be effectively motivated to participate in the collection system and informed in the right way about the possibilities to sort waste. The results of the study demonstrate that consumers prefer to collect and dispose of food waste in a biodegradable bag, which will be available free of charge at the collection point, or in any container they find at home. The study found a high level of willingness to sort food waste; however, this must not incur a financial cost for consumers. Only a third of the municipalities surveyed are willing to bear the financial burden of purchasing biodegradable bags, and more than half of the municipalities would be willing to purchase a reusable bucket for household food waste collection.

The predominant motivation consumers perceive for engaging with a food waste sorting system is to contribute to environmental enhancement and to be assured of the subsequent utilisation of the waste. The most prevalent perceived obstacles pertain to the unfavourable externalities associated with this particular type of waste, namely odour and entomological concerns. Nevertheless, distinctions emerge among diverse consumer demographics, a phenomenon that is further delineated by the segmentation analysis.

Segmentation of consumers is recommended for the effective motivation of FW collection and the accurate targeting of communication in terms of form and content. The segmentation identified four consumer segments, the first of which is characterised by a 'sorting inclined' tendency, representing the younger population under 44 years of age. This segment requires communication specifying operational practical information on how to sort FW (with an emphasis on communication of the correct contents of the collection container). The utilisation of mobile applications or online maps to indicate the nearest available bins, complemented by regular updates on social media which are often used by this age group, can also be recommended. The **second segment**, comprising mainly the middle-aged, slightly above-average-income, university-educated population, is less trusting. It is therefore recommended that the subsequent use of waste to this group of citizens be explained (specific examples in the surrounding area), for example by showing how the treated waste contributes to the production of compost or energy in a local biogas plant. In particular, the use of online communication channels can be recommended to encourage motivation for collection and to reduce perceived barriers. The involvement of interactive educational tools such as videos or webinars to further clarify the meaning of FW sorting is also recommended.

The **third segment** is dominated by younger men who are basically unworried. They are not afraid of obstacles to FW sorting. Communication messages targeting them should support their motivation to participate in the collection system. It is appropriate to focus on competitive elements (e. g. rewards for sorting) and simple communication directly at the collection point (e. g. visual signs or QR codes with additional information), possibly in combination with online channels. The **fourth segment** is constituted predominantly by retired women who perceive numerous barriers to FW collection. In this segment, it is recommended that barriers should be reduced through effective communication, for example by the provision of easily accessible containers in close proximity to their residences, the elimination of odour and insect problems, and the dissemination of regular information on the hygienic treatment of collection points. Motivation is sufficient in this segment; however, it is imperative that barriers do not become overwhelming. The most appropriate method of communication with consumers in this segment is through traditional channels (leaflets, newsletters, etc.) or through community events or meetings that explain the importance of sorting.

The current limitation in implementing a food waste collection and sorting system is the unresolved financial burden of the collection system. Consumers demand convenience and zero costs associated with FW sorting, yet only some municipalities are willing to bear the costs of collection, and usually only partly. This opens up scope for further research in terms of the distribution of the financial burden of the collection and sorting system between municipalities and other waste management actors.

List of symbols

FW Food Waste

MSW Municipal Solid Waste

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Motivace a bariéry spotřebitelů k třídění potravinového odpadu: Role segmentace v komunikaci municipalit

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Souhrn

Poznání motivace a bariér spotřebitelů k třídění potravinového odpadu je prerekvizitou k úspěšné komunikaci obcí s občany. Cílem tohoto příspěvku je odhalit motivaci a bariéry spotřebitelských segmentů včetně identifikace segmentů využitelné pro cílení komunikace obcí s občany. S využitím výzkumného instrumentu ve formě dotazníkového šetření mezi spotřebiteli o velikosti 1332 respondentů bylo možné poznat postoje a preference spotřebitelů, které byly následně doplněny o data z dotazníkového šetření mezi municipalitami. Aplikovaná shluková analýza identifikovala čtyři segmenty. Pro všechny spotřebitelské segmenty je důležitá motivace v podobě vědomí, že bude odpad následně zpracován a zajištění dostatečného množství sběrných nádob. Se spotřebiteli je vhodné komunikovat konkrétní případy využití odpadu a také se vypořádat s negativními externalitami znesnadňujícími sběr odpadu. Percepce bariér sběru a třídění odpadu se napříč spotřebitelskými segmenty liší.

Klíčová slova: *Potravinový odpad, segmenty spotřebitelů, motivace, bariéry, vnímání municipalitami, chování při třídění odpadu.*

The impact of distribution and collection systems on the purity of kitchen waste: A comparative analysis of approaches in Slovakia

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Abstract

This study evaluates the impact of different distribution and collection systems on the cleanliness of kitchen waste (KBW) at the consumer stage, focusing on households in three Slovak cities: Žilina, Bratislava, and Partizánske. The analysis highlights differences between individual housing construction (IHC) and collective housing construction (CHC), assessing contamination levels at the point of waste generation and collection. We utilized a methodology based on manual waste sorting and statistical analysis using Friedman's ANOVA to identify significant differences in contamination levels. The study also examines the influence of distributing compostable bags on reducing contamination and compares the effectiveness of door-to-door and drop-off collection systems. Results demonstrate that door-to-door collection significantly improves KBW cleanliness, with the city of Partizánske achieving the lowest contamination rates. Furthermore, a higher distribution of compostable bags correlates with reduced contamination in CHC. These findings emphasize the importance of consumer-stage interventions and systematic analysis methods in waste management to enhance waste purity and support sustainable waste utilization practices.

Keywords: *kitchen bio-waste, waste collection, compostable waste bags, waste management*

Introduction

Waste is generated by every human activity. It is often associated with something unnecessary, dirty, smelly, or dangerous and damaging to the environment. "Waste is a movable item or substance that its holder discards, intends to discard, or is required to discard in accordance with this law or special regulations".[40] According to § 2 para. 14 of Act No. 223/2001 Coll. on Waste, municipal waste is waste from households arising in the municipality during the activities of natural and legal persons.[39]

The European Union sets an ambitious goal to recycle 55 percent of solid municipal waste by 2025, with separate waste collection being a crucial prerequisite for achieving this goal. According to Directive 2008/98/EC, the term "biowaste," as a component of separated collection, includes "biodegradable waste from gardens and parks, food and kitchen waste from households, offices, restaurants, wholesale markets, canteens, catering establishments, and comparable waste from food processing plants." In the EU, from December 31, 2023, at the latest, "biowaste must be separated and recycled at source or collected separately and not mixed with other types of waste".[8] According to calculations by the European Topic Centre for Sustainable Consumption and Production (ETC/SCP), biowaste constituted 37% of municipal waste in Europe from 2008 to 2010.[12]

According to Pepicha (2010), waste and secondary raw materials generated during the cultivation and processing of plants and animals are called biomass. Biomass can be divided into phytomass and zoomass.[22,27] Biomass can be suitable for combustion, biofuel production, or biogas production with subsequent combined heat and power generation[16]. The use of biomass can vary depending on the source, processing method, and the product obtained from it. Many existing technologies produce abundant organic fertilizers, generate energy, or use it as an alternative fuel source from biodegradable waste.[30]

From forestry and agricultural biomass, we can obtain firewood, wood chips, briquettes, or pellets through cutting, drying, pressing, or chipping. Processing can yield heat and electricity. Carbonization can produce charcoal, and gasification can produce syngas. Pyrolysis produces pyrolytic oil or gas. Liquefaction, esterification, and fermentation can produce liquid fuel, biodiesel, or bioethanol, used in transport or for heat and power generation. Processing of biological waste from animal husbandry, food production, green biomass, and biodegradable municipal waste can yield biogas or syngas for heat and power generation.[26]

Another source of biomass is municipal waste. The corresponding biodegradable part of municipal waste is called biomass. It is one of the most universal and widespread sources of energy. Biomass is biodegradable municipal waste, mainly kitchen and restaurant waste and waste from parks and gardens[27]. Waste biomass from wood-processing facilities (such as sawmills, carpentry workshops, etc.) is particularly suitable for energy production. Other suitable biomass sources in rural areas include agricultural crops and their residues (straw, corn stalks, and plant tissues). Every municipality has public spaces that need to be maintained (e.g., parks, playgrounds, cemeteries). A source of dendromass is the spring and autumn pruning of trees in orchards and parks. Not less significant are private lands of residents and their kitchen waste. Approximately 1 billion tons of food waste is produced worldwide annually, posing a major challenge for waste management.[9] Creating suitable conditions for collecting and separating such biomass provides an additional source.[17]

Various processing technologies for the biodegradable part of municipal waste can produce various products.[28] Composting is a natural, controlled, predominantly aerobic biochemical process in which living organisms, particularly microorganisms, convert original organic matter into organic fertilizer (compost)[4]. Home composting means composting biowaste and using compost in gardens belonging to private households. Community composting means composting done by a group of people in a specific location to collectively compost their biowaste generated in that area. The resulting compost is used for the community's own needs. Municipal or industrial composting means composting biowaste from a larger collection area at a central composting facility. The compost can be used for personal needs or sold[6,29]. Various composting methods include pile composting, vermicomposting, or box composting.[28]

Anaerobic digestion is a controlled process of decomposing biodegradable waste and biomass without air access, resulting in biogas and an undecomposed residue called digestate[33]. Biogas is a mixture of gases containing 55 – 75% methane, 23 – 43% carbon dioxide, and approximately 2% hydrogen. Other gases present in trace concentrations include hydrogen sulfide and other sulfur and nitrogen compounds. Digestate is the fermented residue from the process and can be used as an organic fertilizer on agricultural land[18]. Adding digestate to the soil can promote plant growth by providing essential nutrients such as nitrogen (N) and phosphorus (P).[14]

The use of biomass is affected not only by its source and processing but also by its level of contamination. Given the quantity and widespread use of plastics, plastics have become a global biomass pollution source. In recent years, concerns have risen regarding environmental pollution related to microplastics (particles smaller than 5 mm)[3]. These particles are found throughout nature, including in aquatic environments, densely populated areas, and uninhabited places like Antarctica[8]. According to Wang et al.[35], soil may contain 4 to 23 times more microplastics than oceans. In addition to ocean water, microplastics are present in wastewater and sewage sludge.[20,21,25,35] Such pollution can pose serious environmental risks, such as jeopardizing soil quality and affecting plants, animals, and humans. Microplastics are not a single material but a mixture of various plastics and substances (e.g. stabilizers, flame retardants, or environmental toxins and metals adsorbed on their surfaces), which can be harmful upon ingestion, causing abnormal behavior, growth, and reproductive issues[40]. Other studies have shown negative effects of microplastics on soil, affecting animal and microbial activity in the soil. It has also been found that microplastics impact soil's water-holding capacity.[7,37]

Energy processing of biomass or its processing into fertilizers or compost can lead to the transfer of microplastics and other contaminants into the environment. On the other hand, the presence of non-biodegradable components in biomass increases the cost of its processing. Most countries allow certain amounts of impurities like plastics, glass, and metals in fertilizers (0.3% dry weight for each type of impurity and 0.5% dry weight for the total sum[11]. Several studies show that digestate and organic fertilizers from household biowaste fermentation may contain large amounts of microplastic fragments, while fertilizers from agricultural biogas plants and green composts are less contaminated with plastics. Such contamination could result from improper bio-waste sorting by residents and collection by municipalities.[21,31,36] Plastics can enter the soil through plastic mulching or the application of soil supplements containing plastics. Up to 2.38–1,200 mg of plastics per kg have been found in compost so far, while plastic concentrations in sewage sludge range from 1,000 to 24,000 plastic pieces per kg [3].

Braun et al.[41] concluded that compost application should be considered a potential source of plastics for both agricultural and horticultural soils, emphasizing the need for technical solutions to minimize the risks of this contamination while continuing this practice as an important means of ensuring soil health.[41] In industrial composting, manual sorting, mechanical sorting, or air sorting is used to remove plastics from compost.[47] If composting is to expand, it must become profitable and ideally competitive. On the other hand, the time and costs associated with plastic removal currently hinder profitability.[46] Addressing plastic-related issues is one of the milestones of the European Green Deal[45], which identifies the bioplastics industry as one of the potential solutions. Biodegradation depends on the chosen degradation technique and environment, so an optimal biodegradation method must be selected for each biodegradable bioplastic.[44] According to § 81 of the Waste Act (effective from January 1, 2021), municipalities are obligated to separate kitchen waste from households. However, this obligation does not specify a particular method of collection, such as the use of compostable bags. Currently, there is no consensus among stakeholders (i.e., EU member states, manufacturers, waste operators, NGOs) on how waste should be collected and processed. As a result, various approaches to waste management exist, even at local and regional levels, causing confusion and skepticism among consumers.[42] The European standard EN 13432 specifies the requirements and criteria for packaging that is compostable and biodegradable. The standard is used to certify packaging, including compostable bags intended for industrial composting.[43,45]

The aim of this study was to evaluate three different types of kitchen waste (KBW) collection and distribution in the cities of Žilina, Bratislava, and Partizánske. Additionally, we addressed the differences between individual housing construction (IHC) and collective housing construction (CHC). Finally, we assessed KBW contamination in the Bratislava Lamač district a year after KBW sorting was introduced and the impact of distributing compostable (degradable) bags on waste by the municipality.

Material and Methods

The research was conducted in three cities (Bratislava, Partizánske, and Žilina). These cities were selected based on available options, as they are the only ones in Slovakia implementing the observed type of collection and distribution of kitchen waste (KBW) and the only ones that underwent an analysis of sorted waste to the required extent. The analysis of mixed municipal waste (MMW) was based on the legislative guidelines of the Ministry of Environment of the Slovak Republic, which, according to § 105 para. 3 letter a) of Act No. 79/2015 Coll[38]. on Waste and amendments to certain laws, establishes the methodology for analyzing mixed waste in § 1. The analysis of MMW is based on the principles of the legislative guidance of the Ministry of Environment of the Slovak Republic, as defined by § 105 para. 3 letter a) of Act No. 79/2015 Coll[40]. on Waste and amendments to certain laws. Since there is no ministry methodology for kitchen waste (KBW), we used our own methodology based on similar principles. In each selected locality, we analyzed samples of MMW and KBW separately from individual housing construction (IHC) and collective housing construction (CHC). Individual housing construction (IHC) includes single-family houses inhabited by one family, while collective housing construction (CHC) consists of apartment units, each occupied by a separate family, often forming residential complexes. Each of the analyzed cities has its own individually tailored waste collection system (Table 1). For both types of waste, containers were selected from various streets and neighborhoods within the municipal district. In each type of housing, we followed the rule of always taking both containers from one family home collection point, both the MMW and the KBW containers. Containers with non-standard waste or a non-standard quantity of any waste component were excluded when selecting collection containers for sampling. The physical selection of containers was carried out by collection workers. The sample size was designed so that the total weight for MMW (CHC and IHC) ranged between 500 kg and 1 ton. The number of containers for KBW was identical to the number of containers for MMW (applies to both IHC and CHC), as mentioned in the pairs of containers from the same family home collection point. The analysis of samples from each selected municipal district took place at four collection points (MMW from CHC, MMW from IHC, KBW from CHC, and KBW from IHC). For MMW, we sorted it into three components: KBW, garden biowaste, and mixed municipal waste. Each component was placed separately into bags, then weighed, and the weight of each bag was recorded. During the evaluation, the recorded weights of each component were summed. Their sum represented the total weight of the analyzed component of waste from one type of housing. Then their percentage share was determined. KBW was sorted into two basic components (biodegradable waste and non-biodegradable waste) (Figure 1). The European standard EN 13432 specifies the requirements and criteria for packaging that is compostable and biodegradable, intended for industrial composting. In our study, compostable waste bags were categorized under biodegradable waste and were not analyzed further. We followed the same evaluation procedure as for MMW analyses.

Data were statistically processed using the STATISTICA software (StatSoft Inc, 2011). Using the Shapiro-Wilk test, we found that the dataset did not have a normal distribution. We used Friedman's ANOVA to compare the average values of the analyzed data.

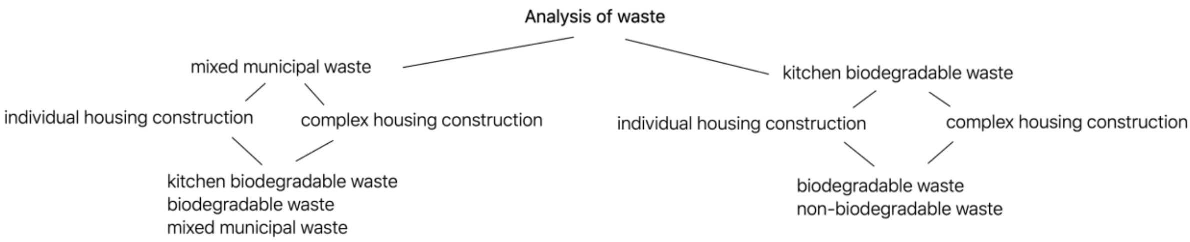

Figure 1: Waste Analysis Scheme (*Figure processed by the authors)*

In the individual cities, several interventions were conducted related to the distribution of bags, an information campaign, and waste collection. Compostable bags for sorted collection were distributed for one year (city of Bratislava), for one month (city of Žilina), and continuously as needed (city of Partizánske). In Bratislava and Žilina, after running out of compostable bags, residents can visit the city office, which will issue them additional bags. In Partizánske, door-to-door collection of kitchen waste (KBW) and distribution of compostable waste bags is done directly to residents' doors as needed. The door-to-door collection system involves residents placing 10-liter waste containers outside their apartment doors, where a city worker collects and empties them. The empty container is left at the resident's door. In individual housing areas, the city provides home composters. In Bratislava and Žilina, there is a drop-off collection system where residents place waste into the nearest container at the collection point designated for sorted kitchen waste (drop-off collection system). The frequency of container collection for sorted waste was twice per week throughout the year, with only once per week in winter in Bratislava (Table 1). Education of residents about the collection system was carried out through door-to-door campaigns (distribution of leaflets, waste bags, waste bins for collecting KBW, individual oral explanation of the collection system), internet campaigns, and distribution of educational materials—leaflets via email and placement in residents' mailboxes. Each city implemented a different type of educational campaign (Table 1). The kitchen waste from the studied cities is processed at the biogas plants of contractual partners. Kitchen waste from Partizánske is transported to the composting facility in Partizánske. Waste from Žilina is processed at the biogas plant in Žiar nad Hronom, while kitchen waste from Bratislava is processed at the composting facility in Horný Jatov (Information provided by JRK Slovensko s.r.o).

Table 1: Basic Data on the Collection and Distribution System in the Monitored Cities (BA- Bratislava, PE- Partizánske, ZA- Žilina)

Town	Number of bags distributed (pcs)	CHC		IHC		Frequency of collection	Information campaign
		collection system	container size (l)	collection system	container size (l)		
BA	150	delivery	240	door to door	20	2x/week- summer 1x/week- winter	door to door, leaflets and internet
PE	as required	door to door	10	home composters		2x/week- all year round	door to door, leaflets and internet
ZA	24	delivery	240 and 1100	delivery	240 and 1100	2x/week- all year round	leaflets and internet

Source: Data provided by JRK Slovensko s.r.o., processed by the authors

In our study, we evaluated three different types of collection and distribution systems for kitchen waste (KBW) in the cities of Žilina, Bratislava, and Partizánske. We also examined the differences between individual housing construction (IHC) and collective housing construction (CHC) in five districts of the city of Bratislava. Lastly, we assessed the contamination of KBW in the Bratislava Lamač district one year after the introduction of KBW sorting and the impact of the distribution of compostable (degradable) bags on waste by the municipality.

Results

IHC Analysis

The analysis of KBW for individual housing construction (IHC) in the city of Partizánske (PE) was not conducted, as KBW collection does not take place in IHC in this city. The city provided residents in IHC with home composters, and KBW is composted by residents in these. In the analysis of KBW from IHC in the monitored cities (ZA and BA), we found that total contamination of KBW with non-degradable components was 0.40% in Bratislava (BA) and 0.58% in Žilina. This difference was not statistically significant. In further analysis, we assessed the share of paper and non-degradable bags; no paper bags were found in KBW in either city. Plastic (non-degradable) bags accounted for 9.57% in Bratislava and 59.17% in Žilina, with the remainder consisting of compostable (degradable) bags. Analysis of the occurrence of non-degradable bags in KBW in Bratislava and Žilina revealed a statistically significant difference in their share ($p \leq 0.001$). The high contamination with plastic (non-degradable) bags in Žilina could have been due to the low distribution of compostable (degradable) bags compared to Bratislava.

CHC Analysis

Basic data on distribution and collection methods in collective housing construction (CHC) and contamination data with non-degradable components in the monitored cities are shown in Table 2. The analyzed data indicate that the drop-off collection system implemented in Bratislava and Žilina negatively impacted the cleanliness of KBW compared to the door-to-door collection system implemented in Partizánske; this difference was statistically significant ($p \leq 0.05$). Based on the analyzed data, we can conclude, as in the IHC analysis, that the more compostable (degradable) bags a city distributes, the lower the contamination of KBW in CHC, and the occurrence of non-degradable bags in this type of waste is significantly lower ($p \leq 0.001$). Furthermore, we demonstrated that the cleanliness of the drop-off collection system is not affected by container size, as this difference was not statistically significant.

Table 2: Comparison of the Purity of Sorted KBW in the Monitored Cities within CHC

Town	Number of bags distributed (pcs) per capita	Collection system	Size of container used (l)	Pollution KBW by non-biodegradable components (%)
Bratislava	150	delivery	240	3.21 %
Partizánske	As required	door to door	10	0.07 %
Žilina	24	delivery	240 and 1100	3.53 %

Source: Data provided by JRK Slovensko s.r.o., processed by the authors

Comparison of KBW Purity in IHC and CHC

In the analysis of five districts (D) in the capital of the Slovak Republic, Bratislava, we found that the average contamination in CHC is 3.21%, while the average contamination in IHC is only 0.40%. In the analysis of KBW contamination in the city of Žilina, we found that contamination in CHC is 3.53% and in IHC 0.58%. These results were confirmed by statistical tests, as statistically significant differences in the purity of KBW from IHC and CHC were demonstrated in both cities ($p \leq 0.001$). No statistically significant differences were found in the comparison between cities.

Based on our findings, we can conclude that there is no statistically significant difference in the purity of KBW in IHC and CHC between the cities of Bratislava and Žilina, even though Bratislava achieves slightly better results. On the other hand, we can state that there is a statistically significant difference in the purity of KBW between IHC and CHC in both cities. The average contamination in IHC is 0.49%, and the average contamination in CHC is 3.37%. When comparing the contamination of KBW from CHC in Partizánske (0.07%) with the contamination in CHC in Bratislava (3.21%) and Žilina (3.53%), a statistically significant difference in favor of Partizánske was demonstrated ($p \leq 0.001$). Based on our findings, we can conclude that the highest purity of KBW in CHC is achieved in the city of Partizánske.

Table 3: Percentage of KBW (non-biodegradable components) pollution in Bratislava, Žilina and Partizánske city districts for IHC and CHC

Town /districts (D)	Priemer (IHC a CHC)	CHC	IHC
Bratislava			
D Lamač	0.87%	1.18%	0.00%
D Petržalka	1.41%	1.48%	0.60%
D Nové Mesto	6.26%	7.02%	0.01%
D Devín	0.87%	-	1.36%
D Podunajské Biskupice	2.94%	3.14%	0.05%
Town average BA	2.47%	3.21%	0.40%
Town Žilina			
Žilina	2.06%	3.53%	0.58%
Town Partizánske			
Partizánske	-	0.07%	-

Source: Data provided by JRK Slovensko s.r.o., processed by the authors

BA- Lamač district Analysis

In further analysis, we focused on the purity of KBW in the Bratislava Lamač district, which we analyzed immediately after the introduction of KBW collection (when residents had access to compostable bags) and one year after the introduction of KBW collection, when residents had used up their compostable bags for KBW and would need to obtain more at the city office. The city of Bratislava distributed compostable (degradable) bags for KBW collection to residents for approximately one calendar year. Afterward, residents could pick up additional bags at the relevant city office. In the analysis of degradable and non-degradable components in KBW in the Bratislava Lamač district, we found an increase in non-degradable components in KBW from 0.41% immediately after the introduction of collection to 1.18% one year after the introduction of KBW collection. This difference proved to be statistically significant ($p \leq 0.05$). On the other hand, we demonstrated a difference between IHC (from 0.47% to 0.00%) and CHC (from 0.98% to 1.18%), also statistically significant ($p \leq 0.05$). We demonstrated an increase in contamination of KBW with non-degradable components one year after the introduction of KBW collection due to the depletion of compostable bags for KBW. Additionally, we demonstrated a statistically significant difference between IHC and CHC in the BA Lamač district ($p \leq 0.05$). The reduction in IHC contamination one year after the introduction of KBW collection, assuming the depletion of compostable bags, may have been influenced by citizens' responsibility and anonymity. KBW collection in IHC is not anonymous, while in CHC, there is high anonymity (it is not possible to identify the resident at the collection container). Since each house has its own container for KBW collection, we assume that residents in IHC behave more responsibly than in CHC. Another factor could be that residents in IHC run out of compostable bags later since they may have home composters that they acquired (Table 4).

Table 4: Analysis of KBW purity in the city of Bratislava-Lamač

Type analysis in district BA- Lamač	Components KBW	Percentage (%)	Date of analysis
1.	Degradable waste	99.59	5.3.2023
	Non-biodegradable waste	0.41	
IHC		0.47	
CHC		0.98	
2.	Degradable waste	98.82	30.11.2023
	Non-biodegradable waste	1.18	
IHC		0.00	
CHC		1.18	

Source: Data provided by JRK Slovensko s.r.o., processed by the authors

Discussion

This extended study is the first in the Slovak Republic to focus on the contamination of kitchen waste (KBW) and the impact of the kitchen waste distribution and collection system on its purity. Based on the analyzed data, we can conclude that the more compostable (degradable) bags the city distributes to residents, the lower the contamination of KBW in CHC. Additionally, the door-to-door waste collection system positively affects the purity of KBW and is statistically significantly better than the drop-off collection system. Similar conclusions have been reached in other studies, showing that cities with door-to-door waste collection sort, on average, 60 kg more dry recyclable materials per resident annually[1].

We further demonstrated that the purity of the drop-off collection system is not affected by the container size but rather by the number of distributed compostable waste bags. Based on our findings, we can state that there is no statistically significant difference in KBW purity between IHC and CHC in Bratislava and Žilina, although Bratislava achieves slightly better results. On the other hand, there is a statistically significant difference in KBW purity between IHC and CHC in both cities.

A similar study has been carried out by researchers in Poland, their study analyses the composition of bio-waste in both urban and rural areas, including differences between areas with single-family houses and apartment blocks. Based on the results, they determined the following composition of bio-waste: food waste accounted for 43.9-56% and garden waste for 27.4-46.3%, with fruit and vegetables making up the majority of food waste. The authors observed the highest level of contamination in waste from residential buildings in urban areas (16.6%). In terms of seasonality, the lowest amount of waste was recorded in winter.[12]

We also demonstrated an increase in KBW contamination with non-degradable components one year after the introduction of KBW collection, likely due to the depletion of compostable bags. A statistically significant difference was found between IHC and CHC in the BA Lamač district. The reduction in IHC contamination one year after the introduction of KBW collection, with the assumption that compostable bags were depleted, could have resulted from the responsibility and anonymity of residents. KBW collection in IHC is not anonymous, whereas KBW collection in CHC is highly anonymous (it is not possible to identify the resident at the collection container). Since each house has its own container for KBW collection, we assume that residents in IHC behave more responsibly than in CHC.

Improving the quality of separated bio-waste was the focus of an Austrian study carried out in ten areas of Styria between 2019 and 2022. The authors found that non-biodegradable plastics (53%) accounted for the highest level of bio-waste contamination, of which plastic bags accounted for the highest proportion. They found higher contamination in winter months compared to summer months. Based on these findings, they implemented various measures and campaigns, with the distribution of paper bags and the threat of increased charges for contaminated waste confirmed as the most effective.[2]

There is evidence that the socio-economic characteristics of the area from which waste is collected can affect the quality of materials, i.e., waste collected from rural areas can differ significantly from waste collected in urban areas, and waste collected from single-family homes may differ from waste collected from complex apartment buildings[19]. The issue of the bio-waste sorting system in Gdynia from the point of view of apartment building residents was investigated by a Polish study after the implementation of the new rules. According to its results, only 15% of respondents correctly classified what belongs to bio-waste and up to 94% of respondents admitted that they throw bio-waste into the mixed waste. They considered the sorting of kitchen bio-waste to be too burdensome. They cited the lack of space for additional bins, the smell of waste and the cost of special bags as other problems associated with the level of sorting. [15] A similar study was also conducted in Spain, where the authors surveyed attitudes towards the willingness to separate bio-waste based on a semi-structured telephone interview. The results showed that approximately 81% of respondents were willing to participate in selective collection of bio-waste. This percentage would increase up to 89% if the municipality provided specific containers and bags for the waste, as the main barrier to participation in the new selective collection system is the need to use specific containers and bags for separating bio-waste.[4]

We did not demonstrate the use of home composters for KBW in IHC in the Lamač district, where KBW collection is in place. We demonstrated more effective KBW collection (in terms of collected waste weight and purity) in IHC than in CHC.

Conclusion

Lastly, we demonstrated highly effective KBW collection (in terms of purity) in CHC in Partizánske. We can conclude that by implementing the same KBW collection system as in Partizánske for CHC and the same KBW collection system as in Bratislava for IHC, a highly efficient KBW collection and distribution system can be achieved. Our research findings are supported by the results of Gwarda and Klopott (2021), who found that in the city of Gdynia, the biofraction collected represents only 9.5% of all collected waste[15]. The most commonly cited reasons for why residents do not sort biowaste were lack of space for another container in the apartment (23%), unpleasant odor (23.8%), and the need to purchase and provide biodegradable waste bags (18.4%). A questionnaire was sent to individuals who failed to meet the obligation to sort biowaste to identify the reasons for non-compliance. Up to 39.6% indicated the absence of free compostable biowaste bags as the reason[15]. Supporting biowaste sorting requires active support from local authorities, both financially and through increasing environmental awareness among residents. Our research findings could be used to support the composition and parameters of waste further and would be suitable for the introduction of waste processing in Slovakia.

Study limitations and future research directions

This study provides valuable insights into the impact of distribution and collection systems on the cleanliness of kitchen waste (KBW); however, some limitations should be acknowledged. Firstly, the study focuses on three cities in Slovakia, which, while diverse in their approaches to KBW collection, may not fully represent all geographic, socioeconomic, or operational differences across the country or internationally. Future research could explore these systems in other regions or countries to validate the findings and assess broader applicability.

Additionally, while the methodology employed manual sorting and statistical analyses to identify contamination levels, the influence of seasonal variations or long-term changes in residents' behavior was not addressed. Further longitudinal studies could provide a more comprehensive understanding of the sustainability and adaptability of different collection systems over time.

Another limitation lies in the assessment of compostable bag distribution. Although a correlation between bag distribution and reduced contamination was observed, a deeper exploration of residents' behavior, such as adherence to sorting guidelines or barriers to participation, would enhance the findings. Future research could incorporate surveys or interviews with residents to gather qualitative data.

Lastly, while the study highlights the advantages of door-to-door collection systems, it does not consider the associated economic or logistical challenges. Comparative cost analyses and environmental impact assessments of different systems would be beneficial in informing policymaking and optimizing waste management strategies.

The study does not describe in detail the use of awareness campaigns in cities due to unavailable information.

By addressing these limitations and expanding on the current research, further studies can build on our findings to enhance the effectiveness and efficiency of KBW management globally.

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Vplyv systémov distribúcie a zberu na čistotu kuchynského bioodpadu: Porovnávacia analýza prístupov na Slovensku

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Souhrn

Táto štúdia hodnotí vplyv rôznych systémov distribúcie a zberu na čistotu kuchynského bioodpadu v spotrebiteľskej fáze, pričom sa zameriava na domácnosti v troch slovenských mestách: Žilina, Bratislava a Partizánske. Analýza poukazuje na rozdiely medzi individuálnou bytovou výstavbou a kolektívnou bytovou výstavbou a hodnotí úroveň kontaminácie v mieste vzniku a zberu odpadu. Použili sme metodiku založenú na manuálnom triedení odpadu a štatistickú analýzu pomocou Friedmanovej ANOVA na identifikáciu významných rozdielov v úrovni kontaminácie. Štúdia tiež skúma vplyv distribúcie kompostovateľných vriec na zníženie kontaminácie a porovnáva efektívnosť systémov zberu „door-to-door“(od dverí k dverám) a „drop-off“ (donáškový). Výsledky ukazujú, že zber „door-to-door“ výrazne zlepšuje čistotu kuchynského bioodpadu, pričom mesto Partizánske dosiahlo najnižšiu mieru kontaminácie. Navyše vyššia distribúcia kompostovateľných vriec koreluje so znížením kontaminácie v kolektívnej bytovej výstavbe. Tieto zistenia zdôrazňujú význam zásahov v spotrebiteľskej fáze a systematických analytických metód v odpadovom hospodárstve na zlepšenie čistoty bioodpadu a podporu udržateľných postupov jeho využitia.

Klíčová slova: *kuchynský bioodpad, zber odpadu, kompostovateľné vrecká na odpad, odpadové hospodárstvo*

Correlation of dissolved hydrogen concentration with VFA/TIC parameter in psychrophilic anaerobic digestion

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Abstract

This paper evaluates the usefulness of measuring the concentration of dissolved hydrogen in an anaerobic fermenter for maintaining the process stability. A laboratory test of two-stage psychrophilic anaerobic digestion of food leftovers from a university canteen was carried out in a vertical reactor with a total working volume of 0.255 m^3 without stirring. In the course of the experiment lasting 1050 days, with an average organic loading of 15.45 kg_{VS} m^{-3} d^{-1} for the 1st stage and 0.657 kg_{VS} m^{-3} d^{-1} for the 2nd stage, a specific biogas production of 0.123 Nm^3 per kilogram of substrate and 0.448 Nm^3 per kilogram of total solids and 0.480 Nm^3 per kilogram of volatile solids, respectively, was achieved. The average methane content in biogas was 55.9 % vol. Slightly higher gas productions were measured in the batch BMP test. The concentration of hydrogen in the mixed biogas from both reactor stages occasionally exceeded 1000 ppm and averaged 134 ppm, the concentration of dissolved hydrogen measured by AMT MS 08 sensor in the overloaded second stage was often 0.10 – 0.23 mg dm^{-3} and correlated with the total concentration of lower fatty acids and with the VFA/TIC parameter. The dissolved hydrogen concentration from AMT instrument was not found to be a reliable timely indicator of overload or process stability.

Keywords: *anaerobic digestion; fermentation; psychrophilic bioreactor; dissolved hydrogen; amperometric sensor*

1. Introduction

Biowaste management is currently a complex and often discussed issue, because many biowaste producers do not know how to properly manage it. In the Czech Republic, in recent years, the annual production of waste from catering establishments has been around 15,000 tons of declared waste, this waste can be disposed of, for example, by composting or anaerobic digestion. According to the Waste Act, every producer of such waste must hand over the waste to an authorized company, which will process it according to available options. For reasons of practicality and speed of disposal, waste was in the past added to livestock or crushed in a kitchen grinder and flushed down the drain. Both options are now prohibited[1].

Catering waste belongs to the group of bio-waste, which is the abbreviated name for biodegradable waste. These are the wastes that are capable of aerobic or anaerobic decomposition. According to Regulation (EC) No. 1774/2002 of the Parliament and of the Council, catering waste can be defined as 'all food waste, including used table oil, originating from restaurants, catering establishments and kitchens, including central kitchens'[2]. Food leftovers from catering establishments are classified in Group 20 (municipal waste) and specifically in Group 20 01 08 - Biodegradable waste from kitchens and catering establishments.

In canteens and catering establishments, especially those that only heat and serve ready-to-eat products, food leftovers represent the largest part of the waste. How to deal with waste such as plastic, paper or glass is a well-known fact. However, how to properly manage waste such as food scraps is not so clear-cut anymore. Act No. 185/2001 Sb. on Waste and Amendment of Some Other Acts[3] has introduced a very strong instrument for reducing the amount of biodegradable waste going to landfill, and the law implies that material recovery always takes precedence over other uses, such as energy recovery. Waste for which no recovery has been found can be disposed of. Landfilling is then the last method of waste disposal. In the case of anaerobic co-digestion with biogas production, this is a material-energy recovery of biowaste, and it is not always clear in advance whether the method is preferable to material recovery in the form of compost for a given biowaste.

Anaerobic digestion process can take place under thermophilic, mesophilic or psychrophilic conditions. The typical temperature range of psychrophilic digestion is up to 20°C [4]. In the anaerobic system, each new batch of substrate is first dissolved and hydrolyzed, while neither organic acids nor hydrogen are produced to a greater extent. In the second phase, the hydrolysis products are acidified, releasing CO_2 and hydrogen. These changes will most noticeably affect the values of the VFA/TIC parameter and the concentrations of H_2 in liquid and gas. In the next phase - acetogenesis, higher acids are broken down to acetic acid, and CO_2 and H_2 are produced again. A steady state occurs only in case of sufficiently intense methanogenesis, during which both acetic acid and H_2 and CO_2 are consumed[5, 6].

The initial steps of the pathway remain the same in thermophilic, mesophilic and psychrophilic digestion; however, with the operating temperature, other active groups of microorganisms appear in the process. The digestion process consists of events that convert organic compounds into more stable compounds with simultaneous release of biogas, which is a mixture of mostly methane and carbon dioxide. The bacterial hydrolysis breaks down complex insoluble organic matter consisting of carbohydrates, proteins, lipids, and fats. The products are soluble compounds such as simple sugars, amino acids, and fatty acids. This is mediated by various hydrolytic bacteria including members of *Bacteroides*, *Clostridium*, *Streptococcus*, which can produce extra cellular enzymes involved in the degradation and solubilization of complex molecules. In the next phase of acidogenesis, acid-producing bacteria belonging to the genera *Bacillus*, *Lactobacillus and Serratia spp* further degrade the soluble substrates into intermediate products. They consist mainly of heavy fatty acids (VFA) and lower acids such as acetic acid, propionic acid, butyric as well as other short-chain fatty acids, alcohols, H_2 and CO_2. The resulting VFAs and alcohols are further converted into acetic acid, carbon dioxide and hydrogen by acetogenic bacteria during the acetogenesis. Acetate-producing bacteria, including bacteria of the genera *Synthrophomonas* and *Synthrobacter*, are responsible for the conversion of the acid phase to acetogenesis and generate acetate, CO_2, protons and H_2 as the main precursors of methanogenesis. Evidence exists that *Clostridium thermoaceticum* may also reduce protons and, hence, produce H_2 under certain conditions. Thus proton-reducing acetogens may also utilize the acetyl CoA pathway for CO_2 reduction. In the final step, methanogenic archaea, for example *Methanosaeta spp*., they use the products obtained from the previous steps (acetate, CO_2 or methylated compounds) as a substrate for the production of methane-rich biogas [4,7,8].

Food waste in the United States include unconsumed food and food preparation residues from residences, commercial establishments such as restaurants, institutional sources such as school cafeterias, and industrial sources such as factory cafeterias. Zhang et al. measured an average methane yield of food waste at 0.435 m^3 per kg of VS after 28 days of digestion at 50 ± 2 °C. The average CH_4 content was 73 vol. %. The biogas yield was 0.465 m^3 per kg of food waste. The resulting lower heating value was 27.2 MJ m^{-3} in average. About 80% of the methane yield was obtained after the first 10 days of digestion [9].

An example of intensive usage of food leftovers and expired food for biogas production can be found in Austria. Here, after collection and sanitation of food scraps and expired food, the material is anaerobically fermented at mesophilic conditions. With an annual feedstock volume of more than 9,000 tons, approximately 1.8 million cubic meters of biogas is obtained. The economy of the whole plant is due to the high degree of conversion of organic matter during the fermentation process (70 – 75% in the first stage and 90-97% in both stages) [10].

The aim of this article is to verify again the usefulness of measuring the concentration of dissolved hydrogen in an anaerobic fermenter with the aim of maintaining the stability of the anaerobic process. This verification was done for different process conditions than previous than the previous example[11]. We would like to verify whether the dissolved hydrogen concentration correlates with the VFA/TIC ratio, which is a commonly used parameter to assess the stability of the anaerobic process. Dissolved hydrogen monitoring could be a useful tool for monitoring and controlling the anaerobic fermentation process, especially when it comes to maintaining stable conditions for the proper functioning of the anaerobic plant.

Dohányos reports in his research that the concentration of hydrogen in the liquid phase in an anaerobic fermenter is common in the range of 0 – 200 mmol m^{-3}, i.e. 0 – 0.2 mmol dm^{-3} (0 – 0.2 mmol/l or 0 – 0.2 mM or 0.4 mg dm^{-3}). Strong et al. tested a low-cost dissolved H2 probe. VFA accumulation and fermenter failure were observed at dissolved H2 partial pressures below 30 Pa, corresponding to 0.68 ppb. ord-Ruwisch et al. demonstrated that the partial pressure of dissolved hydrogen in an anaerobic bioreactor, within the range of 2 – 8 Pa, exhibits a linear correlation with organic overloading of the process. This parameter is a highly sensitive process indicator, capable of detecting both shock overloads and gradual overloading. In the experimental reactor, when the partial pressure of dissolved H_2 exceeded 6.5 – 7.0 Pa, overloading occurred, leading to the accumulation of organic acids. A computer-based control system, which regulated substrate dosing while maintaining a threshold of 6.5 Pa, ensured stable process operation. These findings were validated in a full-scale 600 m³ reactor, where the critical limit was identified as 7.0 Pa [12,13,14].

In 2001, Björnsson et al. [15] addressed the monitoring of dissolved hydrogen concentration, as it is known to be closely related to VFA accumulation, they addressed the direct measurement of hydrogen in the liquid phase. In this study, a supplementary approach to monitoring dissolved hydrogen was investigated including the transfer of liquid hydrogen through a Teflon membrane and detection in gas phase using a Pd metal oxide semiconductor (Pd-MOS) sensor.

Several abiotic factors have been identified that can serve as early warning indicators, including total or individual volatile fatty acid (VFA) concentration and hydrogen concentration[16]. The concentration of hydrogen affects the degradation of many organic compounds and may be a sensitive guide to the metabolic state of biomass degrading wastes to methane. The use of the concentration of hydrogen in the biogas as a process control index should therefore be evaluated in the industrial context. The results demonstrate that during the operation of the digester the hydrogen concentration in biogas remained fairly constant but following three out of four volumetric shock loads the hydrogen levels rose rapidly before recovering to normal levels within a day. Hydrogen is produced at many stages, and by many bacterial species, during anaerobic digestion and is then consumed by the carbon dioxide-reducing methanogenic bacteria. The capacity of the methanogenic bacteria to remove hydrogen is normally far from being saturated. Increased hydrogen levels inhibit the degradation of volatile fatty acids such as propionic and butyric and can also inhibit acetoclastic methanogenesis by *Methanosarcina spp*. Consequently, in the extreme, accumulation of hydrogen leads to an increase in volatile fatty acid concentrations and acidification within the digester. Measurement of hydrogen levels is therefore appropriate in the development of a process control strategy in anaerobic digestion [17].

2. Materials and Methods

2.1. Inoculum

Digestate or more precisely fermenting biomass suspension from the 1st fermentation stage of the agricultural biogas plant Pustějov II (Zemspol Studénka JSc.) operation close to Ostrava city was used as anaerobic inoculum. The suspension was brought in the morning of the test starting day. The suspension was centrifuged on a small industrial centrifuge CHC-61A (BeHo Ltd., Czech Rep.) at 1200 rpm for 10 minutes. Only the liquid fraction containing a solid particle smaller than approximately 3 mm was further used as inoculum. The anaerobic bioreactor was filled with 0.255 m^3 of inoculum.

2.2. Substrate

The leftover food was obtained from the main canteen of VSB-TU Ostrava. These were food leftovers from plates of various meals. The canteen produces in total at least 30 kg of food leftovers every working day. The material consisted really only of uneaten meals from the canteen as the kitchen processes only semi-finished food and does not produce any serious amount of kitchen biowaste. The leftover food is collected daily in a plastic barrel and this is taken away for disposal by an authorized person under a long-term contract. The leftovers contain all foodstuffs and are not separated according to their origin, i.e., leftovers include bones of cooked meat (chicken only) or also leftover salads and desserts (minimum), see Figure 1.

Figure 1: Leftover food from the university canteen of VSB-TU Ostrava.

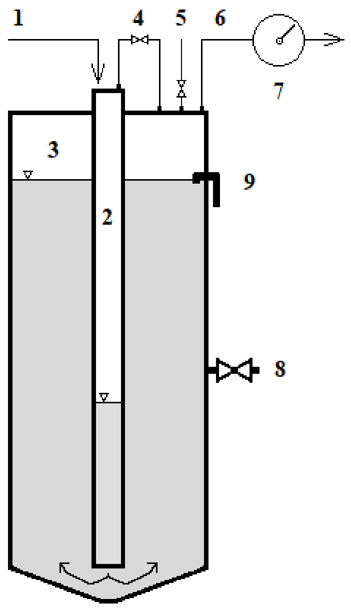
The material was usually only treated by removing large bones and not too forcible mixing with a mortar mixer. It was then stored in a refrigerator at 4 – 6 °C. Occasionally, when the material was too viscous, it was supplemented with a small amount of drinking water. At a later stage, daily batches of material were mixed in a kitchen mixer (25000 rpm) for 30 s. No further adjustments were made. The inoculum and food residue parameters are shown in Table 1. Sampling for analysis was performed only once, at the beginning of the experiment.

Table 1: Inoculum parameters and average parameters of food leftovers.

Parameter	**Symbol, unit**	**Inoculum (start sample)**	**Food leftovers**	**Min**	**Max**	**RSD, %**
pH	pH-H_2O -	7.60	4.63	4.32	5.21	0.5
Total solids (105 °C)	TS, % hm.	4.65	15.59	11.88	19.24	3.7
Volatile solids (Lost on ignition. 550 °C)	VS, $\%_{TS}$	70.1	93.15	91.86	96.95	2.7
Carbon	C, $\%_{TS}$	39.46	46.20		-	
Nitrogen	N, $\%_{TS}$	4.41	2.60			
Ammoniacal nitrogen	N_{NH4+}. $\%_{TS}$	4.03	0.31			
Sulphur	S, $\%_{TS}$	0.63	0.20			
Hydrogen	H, $\%_{TS}$	4.67	6.70			
Oxygen	O, $\%_{TS}$	39.29	40.49			
Ash	CA, $\%_{TS}$	29.90	6.85			
Crude lipids	CL, $\%_{TS}$	1.61	9.08			
Crude fibre	CF, $\%_{TS}$	0.38	1.66			
Crude protein	CP, $\%_{TS}$	1.03	2.36			
Simple carbohydrates	CH, $\%_{TS}$	1.31	2.08			
Starch	ST, $\%_{TS}$	12.34	52.10			
Lignin	LI, $\%_{TS}$	1.94	0.44			
Nitrogenous substances	NC, $\%_{TS}$	8.03	14.63			
Non-nitrogenous extract substances	NFE, $\%_{TS}$	57.86	69.20			

2.3. Psychrophilic two-stage anaerobic digestion of food leftovers

The digestion experiment was carried out in a vertical stainless-steel (AISI 304) bioreactor with a total volume of 0.276 m^3 (see Figure 2). The reactor had two reaction stages. The 1st stage with a working volume of only 0.010 m^3 was formed by axially placed vertical tube with 100 mm internal diameter. This tube was open at the bottom, close to the bottom of the reactor. The 2nd stage was formed by the cylinder with 500 mm internal diameter. The food leftovers were dosed once per day almost every working day. The feeding port was at the top of the 1st stage tube and the digestate overflow was at the level of the batch in the 2nd stage, so the digestion process was semicontinuous. No stirring device was used. There was also no heating device so the fermentation temperature fluctuated slowly in the psychrophilic range (16-26 °C) depending on the actual temperature of the laboratory. The temperature of meat in the batch in the fermenter was 21.3 °C. During the day, the dose of fresh food leftovers hydrolyzed and acidified in the top part of the 1st stage tube and the released CO_2-dominated gas forced slowly the semi-digested suspension down and into the 2nd stage cylinder. In the 2nd stage the process continued mainly with methanization. Some more difficult-to-decompose particles sank to the bottom, where apparently the sludge was strongly anaerobic, and other particles rose to the surface. Spontaneous overflow of the excess volume of digestate occurred continuously through an overflow tube at the surface in 2nd stage. Before daily measuring and feeding gas pressure of both stages had to be equalized though the specialized gas pipeline. This formed mixed sample of biogas. Portable analyzer was used for this mixed biogas composition measurements. Subsequently, the lid of the 1st stage was opened and a new batch of substrate was inserted. Initially, 0.1 kg of food leftovers per day was dosed, but gradually the dose was increased to 2.7 kg per day (occasionally up to 4.4 kg per day). The digestate was sampled at half height of the 2nd stage.



1 – Feeding port

2 – 1st stage reactor tube

3 – 2nd stage reactor cylinder

4 – Pipeline for equalizing biogas pressure

5 – Biogas composition measurement port

6 – Biogas outlet port

7 – Drum-type gas flow meter

8 – Digestate sampling port

9 – Digestate overflow pipe

Figure 2: Two-stage psychrophilic anaerobic bioreactor.

2.4. Analyses

To control the digestion process three parameter of food leftovers were analysed regularly. It was the pH value determined potentiometrically using a WTW 340i with a SenTix 41 probe at 20 °C[18], the total solids content (TS, by drying at 105 °C in an O_2 atmosphere to constant weight, 2.0% RSD) with a KERN DLB 160 3A moisture analyzer with halogen lamp[19] and the volatile solids content (VS, by igniting at 550 °C in O_2 atmosphere to constant weight, 5.0 % RSD) with a LECO TGA 701 thermogravimetric analyzer[20]. These three parameters were analysed also in the digestate samples.

The elemental composition of the solids of inoculum, randomly sampled food leftovers and of the final digestate (C, H, N, S) was determined with a LECO Truspec CHN 628 + S 628 analyzer[20]. The oxygen content was calculated from the other elements according to the ASTM standard[21].

The ratio of the concentrations of total organic acids, primarily less volatile fatty acids (VFA), to residual buffering capacity, represented by total inorganic carbon (TIC), in the digestate was determined using the automatic titrator TIM BIOGAS V02.2 (Hach Lange, Germany), that we recalculated according to the formulas from the study[22]. The concentration of molecular hydrogen dissolved in the suspension was measured using a microamperometric sensor AMT MS 08 (AMT Analysenmesstechnik GmbH, Germany), with a probe range of 0–3.0 mg dm^{-3} and specified for temperatures between 0 – 40 °C. The H_2 sensor was equipped with its own separate temperature sensor and was calibrated daily according to the accompanying documentation. Both sensor probes were placed approximately 30 mm below the surface of the digestate during measurement. After measuring the dissolved hydrogen concentration, a sample of the digestate (approximately 0.9 times the volume of the substrate dose) was taken for analysis, and a new dose of substrate was. The higher heating value of the solid of digestate was determined with a semi-automatic isoperibolic calorimeter LECO AC 600 according to EN 15170[10].

Every working day, volumetric biogas production was recorded according to the conditions in the water-filled drum-type gas flow meter (RITTER TG05, Germany). The biogas composition was analysed using a BIOGAS 5000 portable analyzer (Geotechnical Instruments Ltd., UK) with a dual wavelength IR sensor for measuring methane (CH_4 0 – 100 % vol.) and carbon dioxide (CO_2 0 – 100 % vol.), and an electrochemical sensor for the determination of hydrogen gas (H_2 0 – 1000 ppm), hydrogen sulfide (H_2S 0 – 5000 ppm) and oxygen (O_2 0 – 25 % vol.). Missing data were interpolated linearly.

Other parameters used to describe the anaerobic digestion process are Organic Loading Rate (OLR) and Hydraulic Retention Time (HRT). The OLR parameter indicates the capacity of the anaerobic digestion system to convert organic matter into biogas.

$$OLR\ [kg/m3/day] = \frac{Mass\ of\ Organic\ Substrate\ [kg/day]}{Reactor\ Volume\ [m^3]}$$

The HRT parameter indicates the time the feedstock remains in the fermenter in anaerobic digestion systems.

$$HRT\ [days] = \frac{Volume\ of\ Digester\ [m^3]}{Influent\ Flow\ Rate\ [m^3/day]}$$

2.5. Biochemical methane potencial test

Simultaneously with the long-term experiment in bioreactor two batch tests of biochemical methane potential (BMP) were performed. The aim of the tests was to verify the practically achievable gas yield from food leftovers under different temperature conditions. Both tests passed without reactor stirring. Glass reactors with the total individual volume of 1.2 L topped with ground glass were used. Each reactor was closed with gas measuring burette with the total volume of 1.4 L. Reactors were placed and heated in water bath inside laboratory hood. Burettes stood in the hood. One test was conducted at mesophilic temperature (40 °C ± 0.5 °C), the other at psychrophilic temperature (20 °C ± 2 °C). Each test was performed at three different initial substrate loads, with the overall lowest load used only under psychrophilic conditions and the highest load only under mesophilic conditions. The conversion of the gas volume to normal conditions (0 °C, 101325 Pa) was based on the temperature and barometric pressure in the hood. In each test, two reactors were used to measure endogenous biogas and methane production (inoculum production) and two reactors contained substrate addition. The BMP standard [20] requires that the VS content of the inoculum is higher than 50% TS and the concentration of VS in the inoculum is in the range of 1.5-2.0% by weight. This means setting the total dry matter TS to the level of 3.0% by weight. The mVS-substrate/mVS-inoculum mass ratio should be in the range of 0.3 – 0.5. With a sufficient volume of biogas in the burette (> 150 ml), the composition of this gas was measured. A Biogas5000 portable analyzer (Geotechnical Instruments Ltd., UK) was used. Data from the CH_4 sensor were used to determine methane production. The data from the CO_2 sensor usually needed to be reduced by 1 – 2 vol. % in order for the sum of volume percentages to be 100%. The theoretical water vapor content corresponding to 2.3 vol. % at 20 °C was included in the sum. Occasional low residual aeration of the sample was subtracted, component contents were corrected. Missing data on biogas volume and composition from weekends were linearly interpolated. The H_2 content was measured to document the low load of the inoculum with acids from the acidification of the organic substances of the substrate. The H_2S content was measured to detect possible inhibition by sulfane or sulfides. The theoretical production of biogas and methane was calculated from the elemental composition of volatile solids according to the Buswell formula modified by Richards, for the case when the released ammonia is dissolved in the suspension and immediately compensated by the carbonate formed from the digestion of produced CO_2 [23].

2.6. Hydrogen concentration correlation

All data were subject to mathematical correlation, specifically VFA/TIC and dissolved hydrogen and hydrogen in biogas data were correlated. The correlation examines the joint variability of two variables and determines whether we can observe a "concurrency" in the data, where higher values of one variable are associated with higher values of the other variable, or, conversely, a "countercurrency," where higher values of one variable are associated with lower values of the other. For this purpose, the concept of covariance is introduced, which measures the strength of the linear relationship between two variables - positive values indicate concurrency in the data, negative values indicate non-continuity, and values close to zero indicate a lack of linear relationship. Therefore, the covariance is standardized with respect to the variances of the variables and in this way the most famous correlation coefficient, the Pearson linear correlation coefficient, is introduced. Pearson's linear correlation coefficient r expresses the degree of linear relationship between two numerical variables. Its values lie in the interval <-1.1>, which greatly facilitates interpretation[24]. Spearman rank-correlation coefficient is a non-parametric correlation coefficient that is robust to outliers and deviations from normality in general, as it, like many other non-parametric methods, works only with the order of the observed values. In contrast to the Pearson correlation coefficient, which describes a linear relationship of the quantities, the Spearman correlation coefficient describes how well the relationship of the quantities and corresponds to a monotonic function, which may of course be nonlinear[25]. The Spearman correlation coefficient describes how well the relationship of the quantities conforms to a monotonic function.

3. Results and discussion

3.1. Process parameters

The anaerobic digestion of food residues was investigated for 1050 days (see Figure 3), with the process being carried out in five phases while maintaining the same process conditions. In the first phase (0 – 45 days), a biogas production of 0.0448 $Nm^3\ d^{-1}$ was recorded with a methane content of 40.3% and an organic loading (OLR) of 8.1 kgVS $m^{-3}d^{-1}$ at a residence time (HRT) of 378 days. The methane production intensity was 0.1 $Nm^3m^{-3}d^{-1}$, with a specific methane production of 0.03 Nm^3kg^{-1}. In the second phase (45 – 210 days), biogas production increased to 0.1147 Nm^3d^{-1} with methane content of 57.1%, while OLR increased to 15.2 kgVS $m^{-3}d^{-1}$at HRT of 205 days. This led to an increase in methane production intensity to 0.3 $Nm^3m^{-3}d^{-1}$and specific methane production to 0.05 Nm^3kg^{-1}. The third phase (210 – 680 days) brought a stabilization of biogas production to 0.1421 Nm^3d^{-1}, methane content was 54.6%, OLR reached 18.3 kgVS $m^{-3}d^{-1}$ and HRT decreased to 178 days. Production intensity remained at 0.3 $Nm^3m^{-3}d^{-1}$and specific methane production increased to 0.06 $Nm^3\ kg^{-1}$. In the fourth phase (680-920 days), biogas production decreased slightly to 0.1369 Nm^3d^{-1}, methane content was 53.8%, while OLR was 17.8 kgVS $m^{-3}d^{-1}$ and HRT decreased to 142 days. Methane production intensity remained at 0.3 $Nm^3m^{-3}d^{-1}$, but specific methane production decreased to 0.04 Nm^3kg^{-1}. In the fifth phase (920 – 1050 days), biogas production decreased to 0.0608 Nm^3d^{-1} while methane content increased to 65.7%. The OLR reached 3.9 kgVS $m^{-3}d^{-1}$ at extended HRT to 399 days, with methane production intensity of 0.2 $Nm^3m^{-3}d^{-1}$ and specific methane production of 0.06 $Nm^3\ kg^{-1}$.

During the 1050 days of the experiment (see Figure 3), the average total solids content of the food leftovers dosed (pH 3.4 – 5.9) was 15.59 wt. %. At an average specific gravity of 1068 kg m^{-3}, the organic content was 93.15 wt.%. At an average organic loading rate (OLR) of 15.45 kg_{VS} m^{-3} d^{-1} the 1st stage worked with an average theoretical retention time (THRT) of 12 days. The 2nd stage worked at OLR of 0.657 kg_{VS} m^{-3} d^{-1} with THRT of 210 days. The reactor as a whole produced 0.123 Nm^3 d^{-1} biogas and 0.069 Nm^3 d^{-1} methane, respectively. The average biogas production per unit mass of wet substrate reached 0.070 Nm^3 kg^{-1}. The CH_4 production per unit mass of total solids input averaged 0.250 Nm^3 kg_{TS}^{-1} and per unit mass of volatile solids input averaged 0.268 Nm^3 kg_{VS}^{-1}. The volatile solids content of the suspension was reduced to 2.40 wt. %, i.e. 84 %, by the process. The average values of the measured and calculated experimental parameters are given in Table 2 and graphically represented in Figure 3 – 5.

Table 2: Average parameters of two-stage psychrophilic anaerobic digestion of food leftovers

Feed parameters	**Mean**	**Min**	**Max**	**RSD, %**
Daily dose weight, kg d^{-1}	1.758			
pH, -	4.63	4.32	5.21	0.5
TS, Wt. %	15.59	11.88	19.24	3.7
	14.54	91.86	96.95	2.7
OLR 1st stage, kg_{VS} m^{-3} d^{-1}	15.452	0.80	61.00	31.4
OLR 2nd stage, kg_{VS} m^{-3} d^{-1}	0.657	0.04	2.82	1.5
THRT 1st stage, d	12	2.4	103.6	55.9
THRT 2nd stage, d	210	59.2	2072.7	1122
Mixed raw biogas parameters				
Daily production, Nm^3 d^{-1}	0.123	0.001	0.287	0.14
CH_4 content, Vol. %	55.9	21.1	77.8	28.6
Digestate parameters				
Temperature, °C	21.30	16.0	26.0	5.0
pH, -	7.43	6.41	8.20	0.9
TS, Wt. %	3.70	2.45	5.00	1.3
VS, Wt. %	2.40	1.38	3.45	1.0

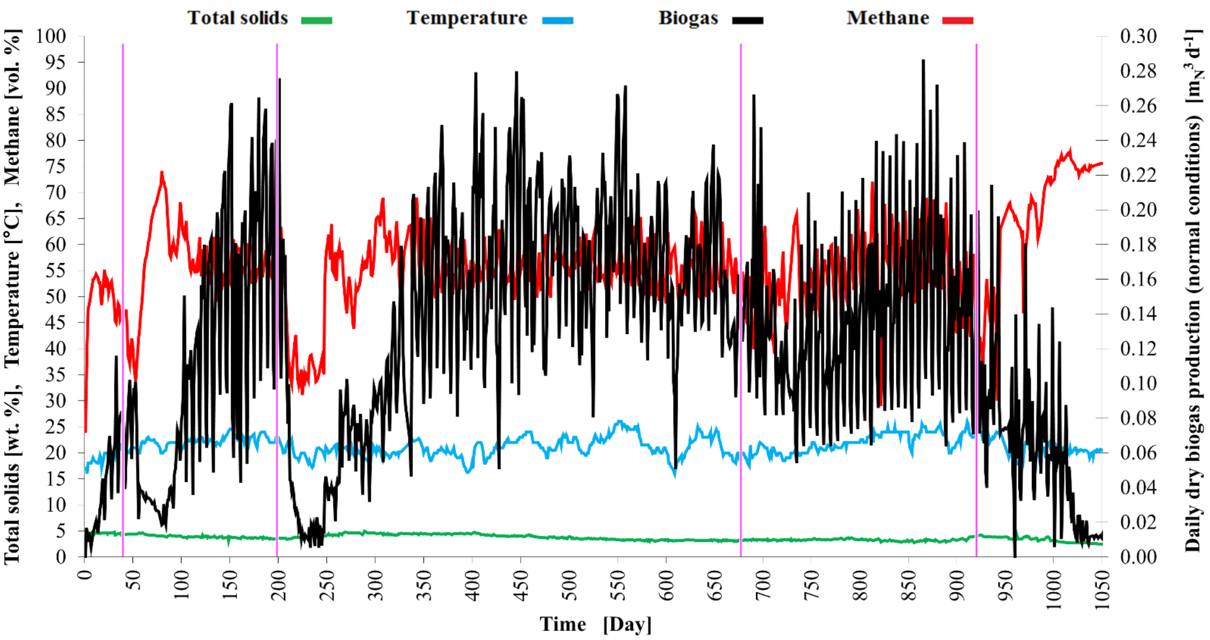


Figure 3: Process temperature, total solids content in the digestate, biogas production and methane content

The curve of daily biogas production in Figure 3 shows that four overload crisis periods occurred during the digestion experiment. The first overload started around the day 30 when the OLR for the 2nd stage increased to 1.2 kg_{VS} m^{-3} d^{-1} and the corresponding THRT shortened under 140 days. Between days 50 – 100 the VFA concentration increased (see Figure 4) and the VFA/TIC ratio was in the interval of lower stability (0.4 0.6). There was high peak of hydrogen in mixed biogas in this period (see Figure 5). This peak was limited by the analyser limit (1000 ppm H_2). The peak of hydrogen concentration dissolved in the 2nd stage slurry (see Figure 4 and 5) did not precede the peak of H_2 in gas or the peat of VFA much. Feeding had to be decreased and a few doses of substrate had to be omitted. After that the digestion process relatively stabilized and biogas and methane production efficiency increased.

The second overload has occurred between the day 200 and 300 when the OLR for the 2nd stage was increased over 2.0 kg_{VS} m^{-3} d^{-1} and the corresponding THRT shortened under 80 days. The VFA concentration increased to similar level like in the first overload period (approx. 8000 mg dm^{-3}) and the maximum of VFA/TIC ratio was 1.0. Highest peak of hydrogen in mixed biogas did not occur soon and was overtaken by the peak of dissolved hydrogen (maximum of 0.21 mg dm^{-3}). This overload period was best signalized by the dissolved hydrogen measurement. During a stable process in the 2nd reaction stage in days 400 600 the concentration of dissolved hydrogen measured by the AMT MS 08 instrument was 0.005 – 0.05 mg dm^{-3}.

The third period of overload has occurred between the day 680 and 800 when the OLR for the 2nd stage was increased over 1.3 kg_{VS} m^{-3} d^{-1} but some doses corresponded to loads of up to 2.5 kg_{VS} m^{-3} d^{-1}. The VFA concentration increased once more to approx. 8000 mg dm^{-3} and the maximum of VFA/TIC ratio was 1.3. Almost all the peaks of hydrogen concentration in mixed biogas were lower (see Figure 5) than these peaks in the period of relative process stability with high methane yield (see days 400 – 600). The rise of dissolved hydrogen concentration was almost continuous (to the maximum of 0.20 mg dm^{-3}) but there were no high peaks at the beginning of overload period that would strongly suggest overloading. This time the better alarm parameter seemed to be the VFA/TIC ratio.

The last overload period started around the day 920. The OLR for the 2nd stage reached 1.8 kg_{VS} m^{-3} d^{-1} in some doses and the corresponding THRT was around 135 days. The VFA concentration went to the extreme (11000 mg dm^{-3}) and the VFA/TIC peak reached 2.5. The only strong peak of hydrogen concentration in mixed biogas come in the day 941 when the VFA/TIC ration was already on the decline. Peak of dissolved hydrogen preceded the peaks of VFA a VFA/TIC by 23 days and had the power to draw attention to the problem. But the dissolved hydrogen concentration was increased from 0.01 mg dm^{-3} to 0.08 mg dm^{-3} long before this overload and yet at this time (days 800 – 850) the reactor reached one of the highest biogas productions with a stable CH_4 content of around 60 vol. %.

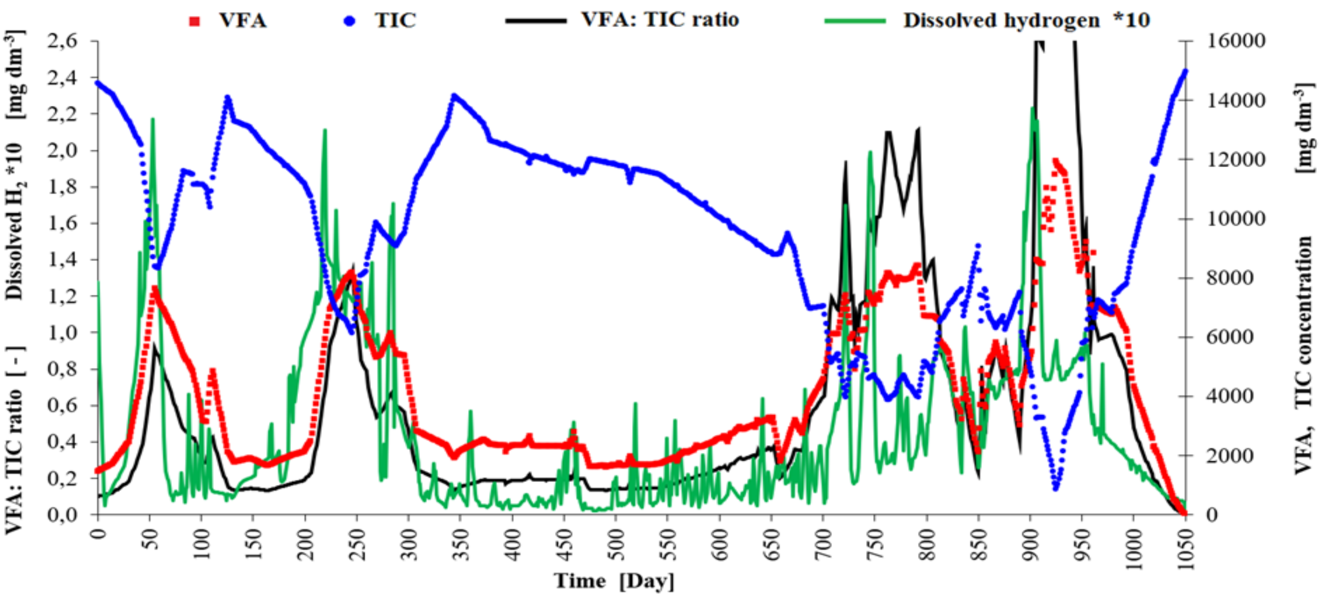


Figure 4: Evolution of the VFA/TIC ratio, its components and dissolved hydrogen concentration

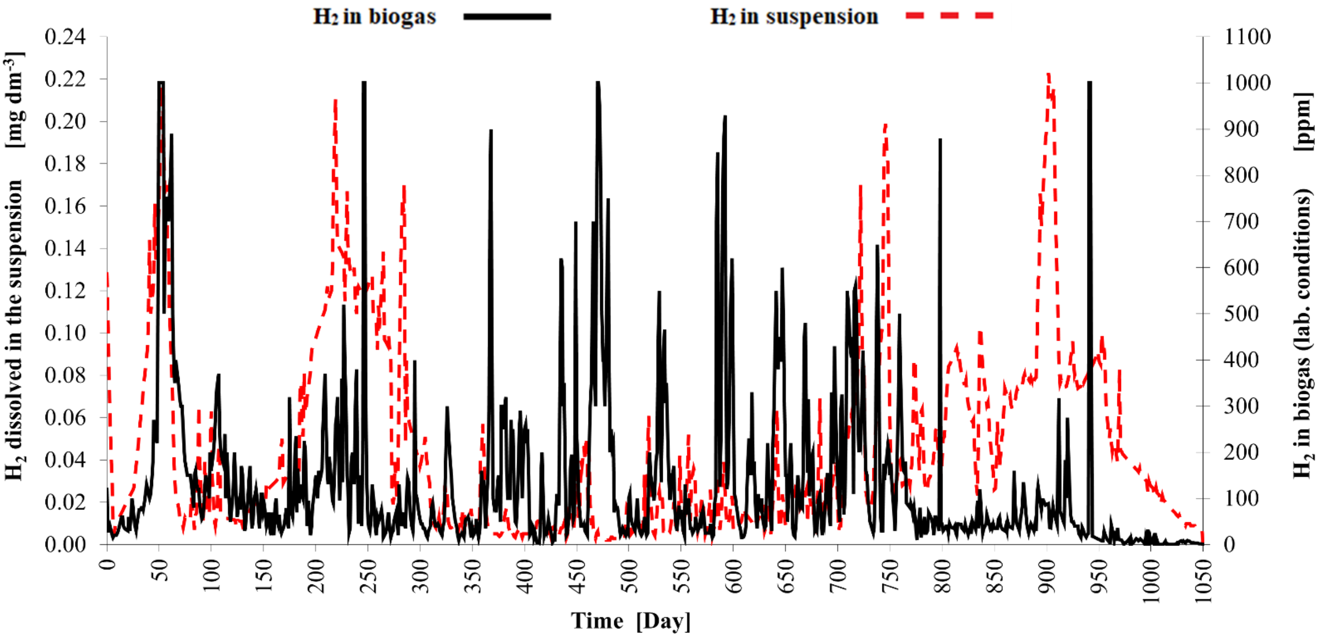


Figure 5: Concentration of H_2 dissolved in the 2^{nd} stage anaerobic slurry and of H_2 in mixed biogas

The Organic Loading Rate values for the 1st and 2nd stages of the process and the dissolved hydrogen concentration are plotted in Figure 6. It is obvious that the OLR curve of the 1st stage is similar to the curve of the dissolved hydrogen curve.

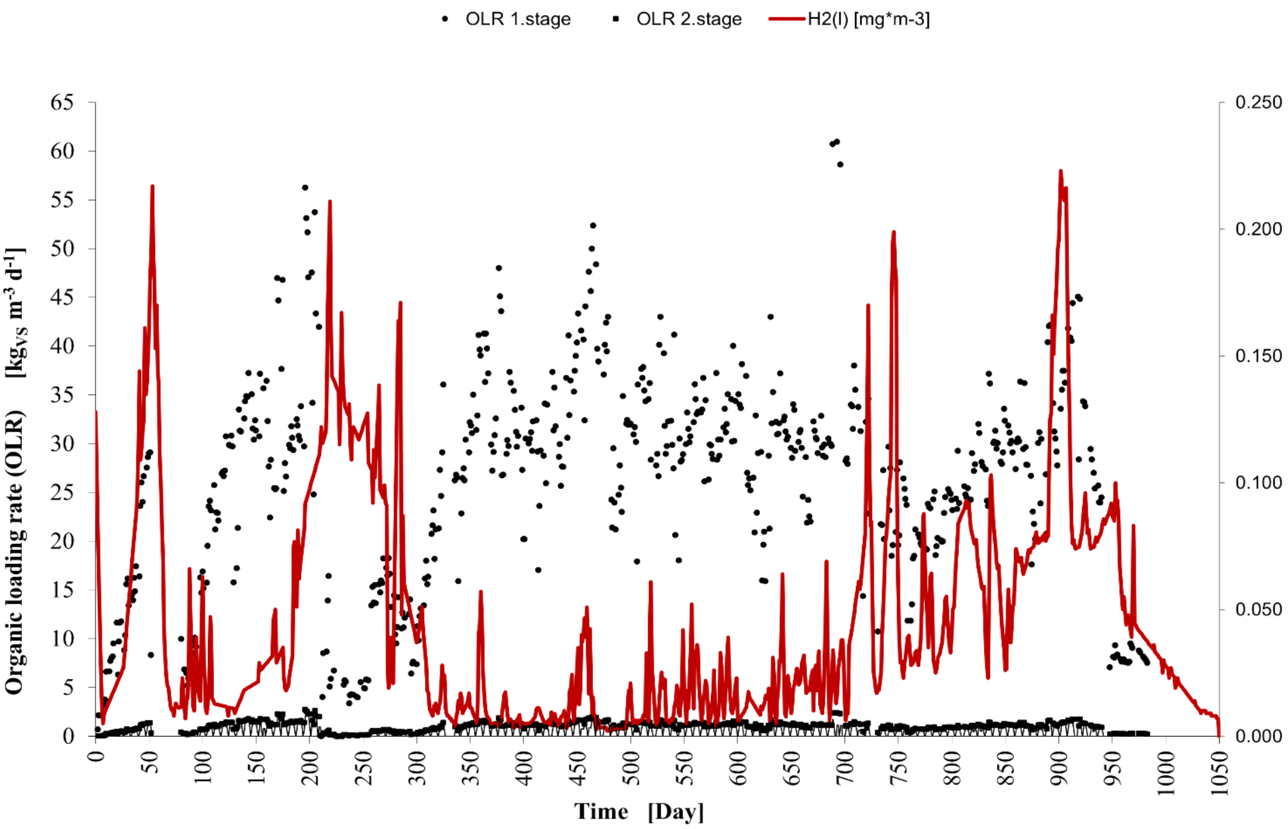


Figure 6: Organic Loading Rate 1st stage, Organic Loading Rate 2nd stage and H_2 dissolved concentration

The H_2S content in mixed biogas increased from 500 ppm over 1000 ppm every time the H_2 content in gas had high peak and this could apparently also cause cross-interference when measuring hydrogen in the liquid and gas phase. The AMT Analysenmesstechnik GmbH stated that their AMT MS 08 instrument has very low interference with H_2S, but sensor poisoning cannot be ruled out during a long-term use in digestate. The only very high peak of H_2S (3800 ppm) occurred during the days 330 – 375. That time the measured content of hydrogen in liquid and gas phase was generally low, VFA/TIC ratio was stable under 0.3 and methane production was increasing quickly so the process was in good balance and inhibition of methanogenesis from H_2S probably did not have a significant effect. pH value in the 2nd stage varied in the range 6.4 – 8.2 and visibly correlated with the course of VFA concentration but the relationship between the change in pH value and the change in biogas or methane production was not clear.¨

3.2. Hydrogen concentration correlation

The correlation analysis between VFA/TIC and the variables H_2 dissolved in suspension and H_2 in biogas was conducted using both Pearson and Spearman correlation coefficients to comprehensively assess the relationships. Figure 7 depicts the results of the cross-correlation analysis which investigates the temporal relationships between VFA/TIC values and both hydrogen concentrations in suspension and biogas at various lags using both Pearson and Spearman correlation methods. We have decided to calculate the correlation coefficients for a 14-days long time span, due to the fact that the trends for all of the correlation coefficients are damped towards the end of this time period thus there would be no meaningful information obtained by calculating the coefficients for higher lag values. The full 1050-day period was used in the cross-correlation analysis, capturing the statistical dependence of these variables across the full timeline. Firstly, no time lag between the correlated parameters was used. The Pearson correlation coefficients for H_2 in suspension and VFA/TIC, as well as H2 in biogas and VFA/TIC, were 0.508 and 0.021, respectively. These values suggest a moderate positive linear relationship between H_2 in suspension and VFA/TIC, while the correlation between H_2 in biogas and VFA/TIC appears to be weak. On the other hand, the Spearman correlation coefficients for H_2 in suspension and VFA/TIC, as well as H_2 in biogas and VFA/TIC, were notably higher at 0.660 and 0.061, respectively. This indicates a stronger monotonic relationship, emphasizing that although the correlation is not strictly linear, there exists a consistent trend in the variables changing together. The discrepancy between the Pearson and Spearman coefficients underscores the importance of considering different aspects of the relationship, as Spearman correlation is less sensitive to outliers and captures nonlinear associations. These results collectively provide a nuanced understanding of the associations between VFA/TIC and the variables H_2 in suspension and H_2 in biogas, shedding light on both linear and monotonic aspects of their relationships.

Our hypothesis was that after introducing a time lag between the measured data of VFA/TIC versus H_2 in gas or VFA/TIC versus H_2 in suspension, a stronger correlation would be revealed. Time lag of 0 to 13 days was tested.

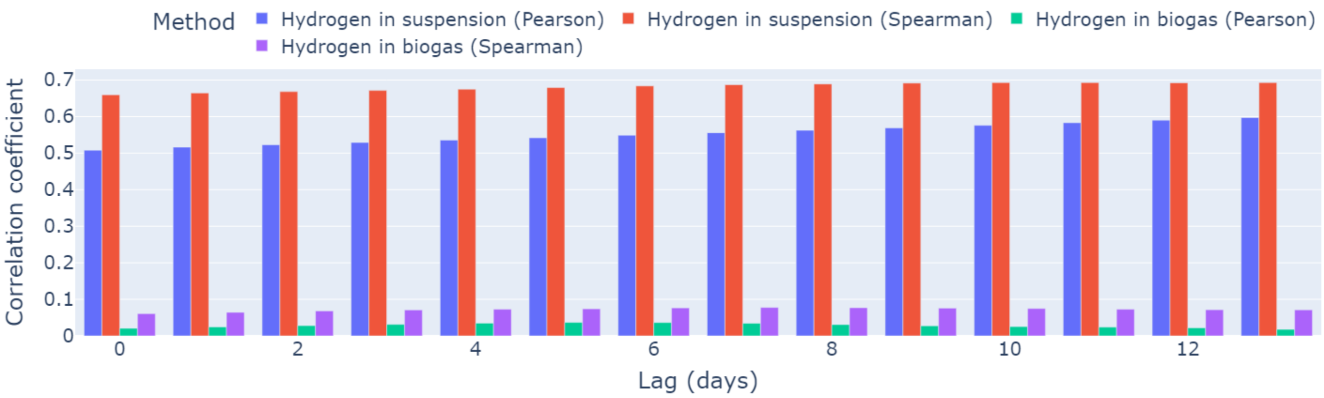


Figure 7: Pearson and Spearman correlation methods

Both Pearson and Spearman coefficients between H_2 in suspension and VFA/TIC show positive relationships across all lags. The Spearman coefficients consistently exceed the Pearson coefficients, emphasizing a stronger monotonic association. The correlations tend to increase slightly with increasing lags. For hydrogen in biogas the Spearman coefficients consistently surpass the Pearson coefficients, however the coefficients values are near-zero, thus the relationship is very weak/non-existent. These results collectively suggest a delayed but persistent positive correlation between hydrogen levels (mainly for hydrogen in suspension) and VFA/TIC, with the Spearman method capturing the overall stronger and more consistent relationship. The increasing trend in correlation with lags suggests a temporal connection between H_2 in suspension and the VFA/TIC ratio in the dataset. While hydrogen production by acidification reactions can in principle be very rapid, especially after hydrolysis of sugars, the decomposition or consumption of acids is highly dependent on the type of acid. For example, propionic acid decomposes very slowly. Consequently, there must be a period when the VFA or VFA/TIC parameter will not correlate with the concentration of dissolved H_2. When individual limiting acid concentrations are exceeded, methanogenic microorganisms are reduced or inhibited, resulting in a further increase in hydrogen concentration.

3.3. Results of BMP tests

The results of both BMP (batch) tests are summarized in the graph in Figure 8 and in the Table 4.

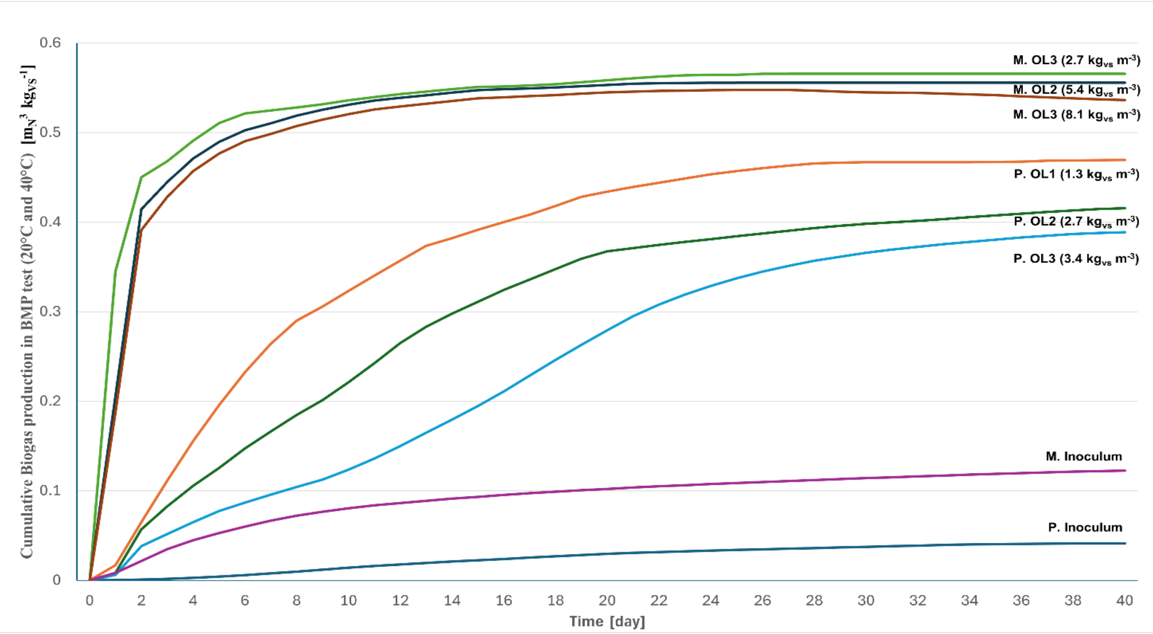


Figure 8: Cumulative biogas production in mesophilic and psychrophilic BMP test

Table 4: Gas production in mesophilic and psychrophilic BMP test of food leftovers

Test (40 days)	**Batch temperature**	**Initial organic load of substrate**		**Biogas production**	**Methane production**	**Methane yield relative to the theoretical maximum**
	°C		$kg_{VS}\ m^{-3}$	$Nm^{-3}\ kg_{VS}^{-1}$	$Nm^{-3}\ kg_{VS}^{-1}$	%
Mesophilic	40 ± 0.5	M-OL1	2.7	0.934	0.565	99
		M-OL2	5.4	0.919	0.556	97
		M-OL3	8.1	0.858	0.535	94
Psychrophilic	20 ± 2.0	P-OL1	1.3	0.839	0.470	82
		P-OL2	2.7	0.714	0.416	73
		P-OL3	5.4	0.685	0.389	68

In accordance with general knowledge, both biogas and methane production decreased with increasing load at both temperatures. An infinitesimal load could theoretically give a gas yield of 100%. Psychrophilic conditions made it possible to obtain 74% and 70% of the methane obtainable under mesophilic conditions, respectively, at a load of 2.7 kg and 5.4 $kg_{VS}\ m^{-3}$.

The food waste was subjected to a single-phase mesophilic and a two-phase psychrophilic anaerobic digestion to identify the effect of the two-phase process and validate the efficiency of psychrophilic technology in converting food waste[12,26]. Both digestion methods proved to be exceptionally effective in converting most of the biodegradable material in food waste into biogas. The single-phase mesophilic CSTR reactor demonstrated high performance in methane production. A relatively high concentration of H_2S does not significantly affect the performance of the mesophilic reactor, provided that no other inhibitory or synergistic effects occur. On the other hand, the high amount of H_2S produced during the process startup appears to be responsible for the increased risk of acidification in the early stages of operation of the psychrophilic two-phase reactor. The system achieves stable digestion and balanced operation within a relatively short period. Despite the limiting effect of low operating temperature, biogas production is not low due to the high hydraulic retention time (HRT) characterizing the two-phase process. Two-phase digestion, even under psychrophilic conditions, is significantly efficient in ensuring a high proportion of volatile organic compounds contained in food waste. The low-temperature two-phase system is much more energy-efficient for processing food waste than the single-phase mesophilic process. Therefore, a two-phase anaerobic digester operating under psychrophilic conditions could be an economically viable option for effectively processing food waste[27].

The fact that the psychrophilic process is more suited to a lower load is also evidenced by the lower CH_4 content in the biogas (56 – 58% by volume) versus 60 – 62% by volume in the mesophile. Psychrophilic hydrolysis and acidogenesis are fast enough to easily overwhelm methanogenesis.

Even at the highest load, the psychrophilic biogas production and CH_4 content in the batch test were slightly higher than when using the two-stage bioreactor, but this was apparently mainly due to periods of deliberate overloading of the reactor. It can be said that the data from the batch test and from the reactor agree.

Measurements of the concentration of dissolved hydrogen from the rest of the meals in the psychrophilic conditions of the BMP test showed the production of high peaks only in the first two days of the experiment. This was followed by a significant drop in hydrogen production. At the end of the experiment, production was practically zero. Changes in the concentration of soluble hydrogen are shown in Figure 9.

BMP biogas production from the BMP test had uncertainty of ± 5 % and the methane production had uncertainty of ± 7 %. But because of high heterogeneity of each storage tank of food leftovers the biogas production could easily vary ± 50 %.

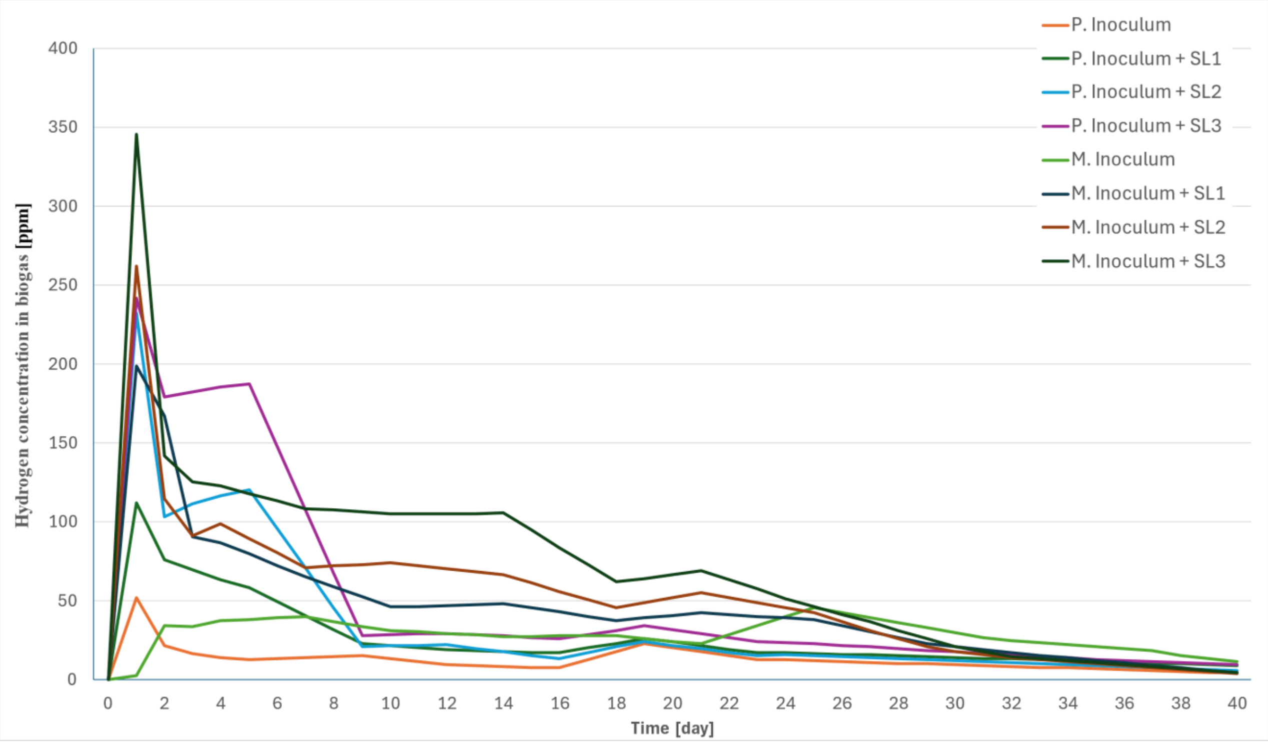


Figure 9: Hydrogen concentration in biogas from mesophilic and psychrophilic BMP test

From the available literature, it has been verified that after the processing of food leftovers or expired food, the gas yield can be described as follows, see Table 5. The production of both biogas and methane in the two-stage reactor under discussion does not deviate from the known limits.

Table 5: Biogas yield in the anaerobic processing of food leftovers

Substrate	Total solids (TS)	Volatile solids (VS)	Biogas yield		CH_4 content	Source
	%	%	$Nm^3\ kg^{-1}$ fresh matter	$Nm^3\ kg_{VS}^{-1}$	vol. %	
Food residues and expired food	9 – 37	80 – 98	0.050 – 0.480	0.200 – 0.500	45 – 65	28, 29
Food residues	23	86	0.100	0.220	n.a.	28, 29
Food leftovers	15.59	93.65	0.0698	0.597	55.9	This study

4. Conclusions

The anaerobic digestion of food leftovers was tested on a long-term basis in a two-stage bioreactor under the psychrophilic conditions without stirring. The process was overloaded four times with a high amount of substrate in order to trace the dependence between known process stability parameters and dissolved hydrogen concentration. Despite drops to blackouts during overload, the average specific production of methane was interesting for practical use. The monitoring of the VFA/TIC parameter in the digestate from the second processing stage was essential for the detection of approaching overloading. Monitoring the hydrogen concentration in the blended biogas from both stages of the process was not very useful. In only one case did a sharp rise in dissolved hydrogen concentration detect overload before a distinct rise in VFA/TIC. The concentration of dissolved hydrogen measured by the AMT MS 08 instrument during a stable process in the 2nd reaction stage was 0.005 – 0.05 mg dm^{-3}. Overall, it can be summarized that the continuous assessment of process stability according to dissolved hydrogen concentration was useful, but not indispensable. Batch tests confirmed still relatively intense digestion of food leftovers under psychrophilic conditions.

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Korelace koncentrace rozpuštěného vodíku s parametrem VFA/TIC při psychrofilní anaerobní digesci

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Abstrakt

Tento článek hodnotí užitečnost měření koncentrace rozpuštěného vodíku v anaerobním fermentoru za účelem udržení stability procesu. Laboratorní test dvoustupňové psychrofilní anaerobní digesce zbytků jídla z univerzitní menzy byl proveden ve vertikálním reaktoru o celkovém pracovním objemu 0,255 m^3, tento reartor pracoval bez míchání. V průběhu experimentu trvajícího 1050 dní při průměrném organickém zatížení 15,45 kg_{VS} m^{-3} d^{-1} pro 1. stupeň a 0,657 kg_{VS} m^{-3} d^{-1} pro 2. stupeň byla měrná produkce bioplynu 0,123 Nm^3 na kilogram sušiny a 0,4048 Nm celkem, 0,448 Nm na kilogram organické sušiny. Průměrný obsah metanu v bioplynu byl 55,9 % obj. Mírně vyšší produkce plynu byla naměřena v dávkovém testu BMP. Koncentrace vodíku ve směsném bioplynu z obou stupňů reaktoru občas přesahovala 1000 ppm a průměrně 134 ppm, koncentrace rozpuštěného vodíku měřená senzorem AMT MS 08 v přetíženém druhém stupni byla často 0,10 – 0,23 mg dm^{-3} a korelovala s celkovou koncentrací nižších mastných kyselin a s parametrem VFA/TIC. Nebylo zjištěno, že by koncentrace rozpuštěného vodíku z přístroje AMT byla spolehlivým včasným indikátorem přetížení nebo stability procesu.

Klíčová slova: *anaerobní digesce; fermentace; psychrofilní bioreaktor; rozpuštěný vodík; amperometrický senzor*

Výsledky pilotního testování zahušťovače kalů v mlékárenském průmyslu

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Souhrn

Tento experiment představuje jeden z přístupů k zahušťování kalů v mlékárenském průmyslu a prezentuje výsledky pilotního testování nového zařízení navrženého k efektivní manipulaci s kalem z čistírenských procesů nejen v mlékárenském průmyslu.

***Klíčová slova:** Pilotní testování, kaly, mlékárenský průmysl, čistírna odpadních vod, zahušťování kalů*

Úvod

Během čistících procesů na čistírně odpadních vod (dále jen ČOV) vzniká přebytečný kal, se kterým se musí určitým způsobem dle platné legislativy na místě vzniku nakládat [1]. Pokud daná ČOV nedisponuje jakoukoli formou kalové koncovky, ve velké většině případů se gravitačně zahuštěný přebytečný kal z čistírenských procesů vyváží fekálním vozem na centrální ČOV vybavenou kalovou koncovkou nebo na bioplynovou stanici [2].

Vyvážení pouze gravitačně zahuštěného kalu je však finančně náročné a náklady na odvoz kalu se mohou meziročně zvyšovat. Fekální vozy při odvozu přebytečného kalu vyváží z velké většiny pouze vodu, celý systém tak postrádá ekonomický i ekologický smysl, protože kal s vysokým obsahem vody odváží vždy velké nákladní vozidlo. Z tohoto důvodu je výhodné pro takovou ČOV nainstalovat jednu z technologií kalové koncovky, ať už se jedná o odvodňovací nebo zahušťovací jednotku. V případě, že je v blízkém okolí možnost likvidovat odvodněný kal, jehož sušina se pohybuje v rozmezí 14 – 30 %, je vhodné na takovou ČOV nainstalovat jednu z technologií odvodnění kalů, například pásový lis, odstředivku, komorový kalolis nebo šnekový lis [3].

Pokud z nějakého důvodu nelze umístit na ČOV jednotku odvodnění kalu, například z důvodu nedostupnosti místa, které by odvodněný kal odebíralo nebo problémům s přepravou odvodněného kalu, může být řešením pouze zahuštění kalu, díky strojové zahušťovací jednotce. Zahušťovací zařízení je schopné zvýšit obsah sušiny kalu na takovou úroveň, kdy kal bude ještě čerpatelný fekálním vozem a kalovými čerpadly. Zahuštěním kalu na maximální možnou úroveň je možné dosáhnout ekonomické úspory a snížit ekologickou zátěž na životní prostředí. Výrazně se sníží objem kalu, který je určen k odvozu a tím se sníží i četnost odvozů fekálním vozem. Mezi další výhody patří například potřeba menších kalových nádrží a snížení emisí při dopravě kalu [4].

Popis zařízení

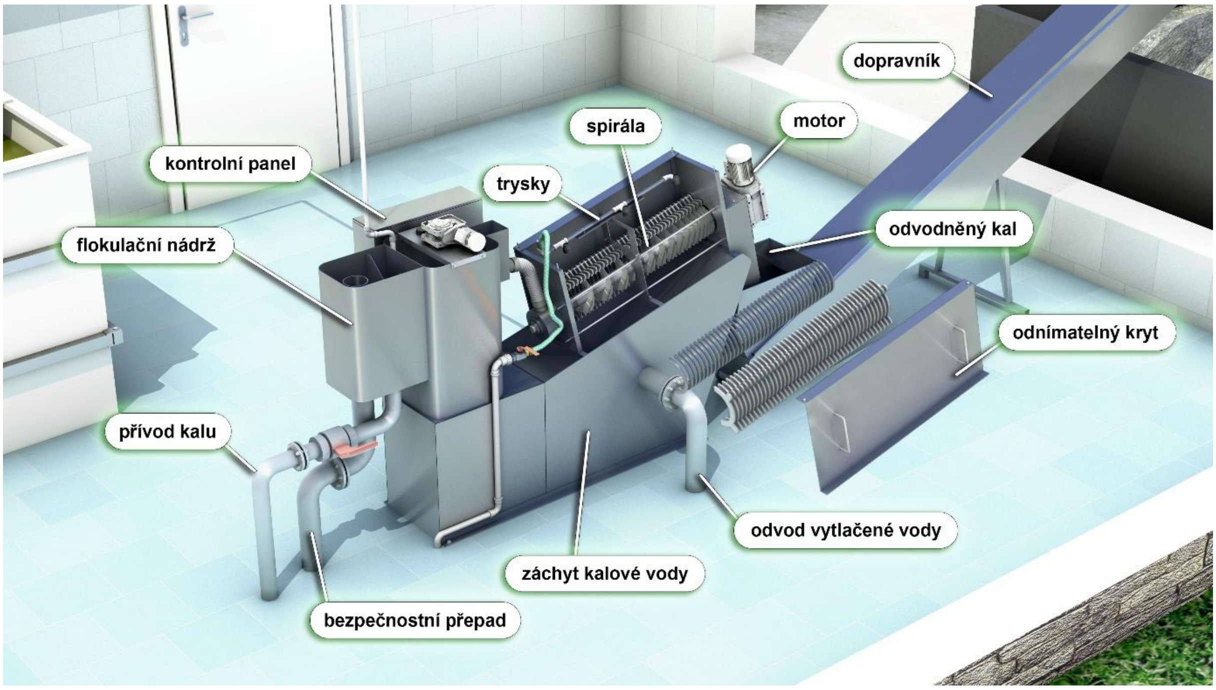
Zařízení AS-DEHYDRÁTOR od společnosti ASIO TECH, s.r.o. je schopné zahustit kal na 5 – 10 % sušiny. Nedílnou součástí zahušťovacího zařízení je stanice přípravy flokulantu, vřetenové podávací čerpadlo, dávkovací čerpadlo rozmíchaného flokulantu a rozvaděč s frekvenčními měniči pro každý pohon zahušťovací jednotky. Zařízení, které je v tomto článku popisováno, je primárně určeno k odvodňování kalů, jak je znázorněno i na obrázku 1. V tomto případě je aplikováno na jiný proces – zahuštění, přestože princip fungování zůstává totožný. Typickou vlastností zařízení je šnekový lamelový princip separace filtrátu a potřeba mít vstupní kal dostatečně homogenizovaný a řádně předupravený flokulací.

Zahušťovací jednotka kalů AS-DEHYDRÁTOR funguje následujícím způsobem: Surový kal z kalové nádrže nebo jímky je čerpán pomocí vřetenového čerpadla do flokulační nádrže zahušťovače. Zde je do surového kalu dávkován roztok flokulantu, který způsobí, že se jednotlivé nerozpuštěné látky v kalu shluknou do kompaktních vloček, které bude snazší odvodnit. Zajistit homogenitu kalu a předúpravu flokulací je nesmírně důležité pro celý zbytek procesu odvodnění, protože bez řádné předúpravy kalu není možné dosáhnout uspokojivých výsledků zahuštění nebo odvodnění kalů. Jakmile je roztok flokulantu řádně smíchaný se surovým kalem pomocí výkonného lopatkového míchadla, je navločkovaný kal přepadem veden do spirály. V této části zahušťovače je umístěná šnekovnice v lamelovém tubusu. Lamelový tubus se skládá z několika desítek lamel, které jsou umístěny střídavě v režimu pevná – pohyblivá. Otáčivým pohybem šnekovnice se navločkovaný kal vynáší směrem k výstupu kalu a zároveň šnekovnice zdvihá pohyblivé lamely, čímž se mezi pohyblivými a pevnými lamelami vytvoří mezera, kterou odtéká voda (filtrát), ale vločky kalu jí neprojdou. Zahuštěný kal na výstupu ze spirály je uskladňován v nádobě na zahuštěný kal nebo je veden dopravníkem k této nádobě.

Mezi hlavní výhody tohoto zařízení patří:

- Nízká energetická náročnost separačního procesu, zejména ve srovnání s odstředivkami,
- Plně automatický a kontinuální provoz, což představuje významnou výhodu oproti komorovým lisům,
- Jednoduchost konstrukce a provozu,
- Menší záběr plochy ve srovnání s pásovými lisy.

Důležitou součástí popisu zařízení je také skutečnost, že lamely jsou v předem nastavitelném režimu pravidelně ostřikovány vodou, což napomáhá udržovat jejich optimální funkci a předcházet jejich zanášení.



Obrázek 1: Schéma šnekového zahušťovače kalu AS-DEHYDRÁTOR

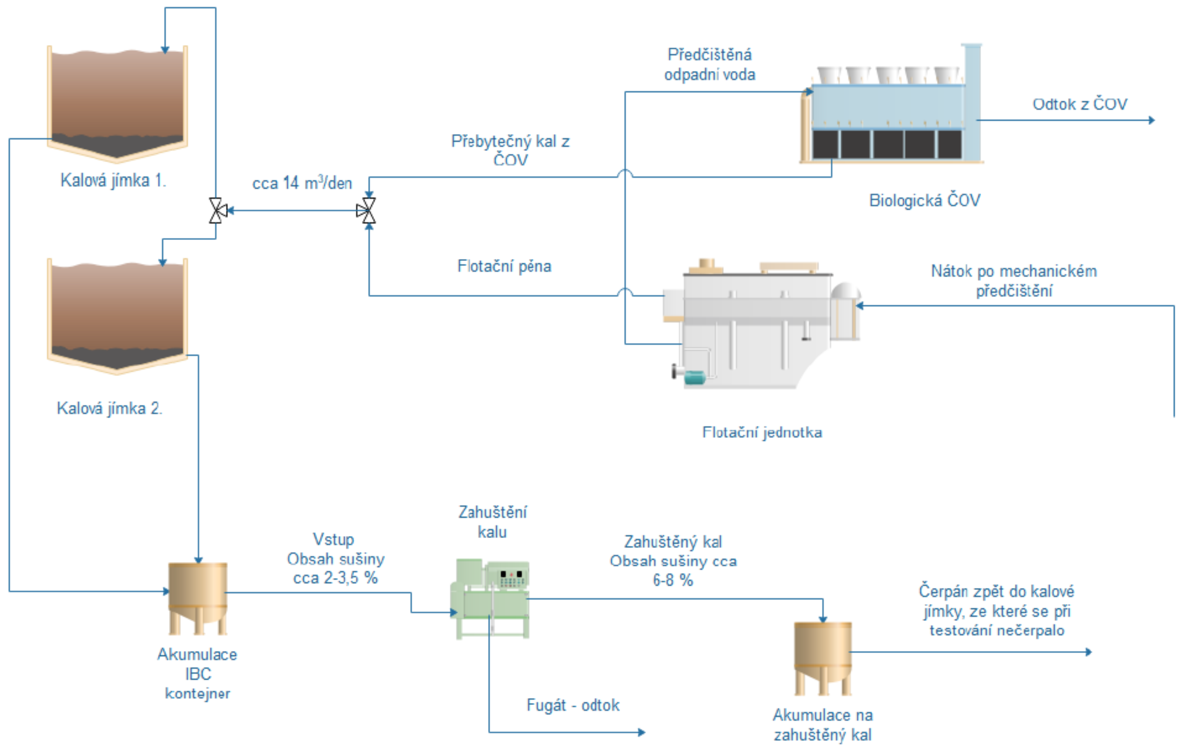
Experimentální část

Pilotní testování probíhalo v mlékárně Milsy, a.s. na Slovensku. Před pilotním testováním probíhala likvidace kalu jeho vyvážením na centrální bioplynovou stanici. Kal byl gravitačně zahuštěn (sedimentace) ve dvou kalových nádrží vybavených provzdušňováním. Po gravitačním zahuštění byl kal následně odčerpán cisternovým vozem. Cisternový vůz kal odvezl na bioplynovou stanici, která je od mlékárny vzdálená 30 km. Četnost vývozu kalu na bioplynovou stanici byla 1 – 2 cisternové vozy denně. Vedení mlékárny vypracovalo zadání pro pilotní testování. Kal bylo dle zadání nutné zahustit na maximální možnou úroveň, tak aby byl stále čerpatelný cisternovým vozem, a výrazně snížit četnost odvozů kalu.

Proces čištění odpadních vod v mlékárně probíhá následujícím způsobem: Odpadní vody z celého areálu, tedy splaškové vody i odpadní vody z výroby mléčných produktů, jsou svedeny areálovou kanalizací na mechanické předčištění. Mechanicky předčištěna odpadní voda je následně čerpána na flotační jednotku. Zde dochází k procesu flotace, ve kterém dochází k separaci kalu a nerozpuštěných látek od vody. Částice kalu a nerozpuštěné látky, jejichž hustota je nižší, než hustota vody jsou unášeny jemnými bublinami vzhůru na hladinu, kde jsou stírány a svedeny do kalových nádrží. Částice kalu a nerozpuštěné látky, které mají hustotu vyšší, než je hustota vody, sedimentují na dně flotační jednotky, odkud jsou v pravidelných intervalech řízeně vypouštěny pomocí odkalovací armatury. Tento sediment je opět sveden do kalových nádrží. Odpadní voda je po procesu flotace gravitačně vedena na biologickou ČOV a odtud je vyčištěná odpadní voda vypouštěna do městské kanalizace. Přebytečný kal z procesu biologického čištění je čerpán do kalových nádrží.

Pilotní jednotka zahuštění kalů AS-DEHYDRÁTOR je velmi kompaktní, protože je celá umístěna na standardní plastové EURO paletě. Jednotka byla po diskuzi s obsluhou ČOV umístěna do objektu ČOV, kde se uskladňuje chemie. Po dobu pilotního testování byl kal z kalových nádrží čerpán do IBC kontejneru, který sloužil jako předřazená akumulační nádrž. Kal byl v kalových nádržích po dobu pilotního testování promícháván dmychadly, aby bylo dosaženo dostatečné homogenizace. Výsledný zahuštěný kal byl čerpán ze strojního zahuštění do připravené mobilní nerezové nádrže, ze které byla dle plánu provedena zkouška čerpatelnosti [5].

V kalových nádržích dochází ke gravitačnímu zahuštění kalu na sušinu 2 – 3,5 %. Testování probíhalo s kalem, jehož stáří bylo v řádech několika dní z kalové nádrže č. 1, ale také s kalem, jehož stáří bylo v řádech několika týdnů z kalové nádrže č. 2. Strojní zahuštění kalu je schopné tento předzahuštěný kal zahustit na sušinu 6 – 8 %, ať už se jedná o čerstvý kal nebo několik týdnů uskladněný kal. Testováno bylo několik typů emulzních i práškových flokulantů. Nejlepších výsledků dosahoval práškový kationický flokulant Zetag 8180 při zohlednění nejnižší spotřeby flokulantu, ta činila 1,8 g/kg sušiny kalu. Při výběru flokulantu je potřeba zohlednit typ, náboj, koncentraci a dávku. Hodnoty vyjmenovaných parametrů se budou s různými kaly měnit. Zahuštěný kal na strojním zahušťovači byl podroben také zkoušce čerpatelnosti cisternovým vozem, výsledkem bylo bezproblémové vyčerpání zahuštěného kalu. Výsledkem celého pilotního testování byla průměrná objemová redukce kalu o 50 % [5].



Obrázek 2: Schéma zapojení zařízení AS-DEHYDRÁTOR do procesů čištění odpadních vod v mlékárně

Výsledky a diskuze

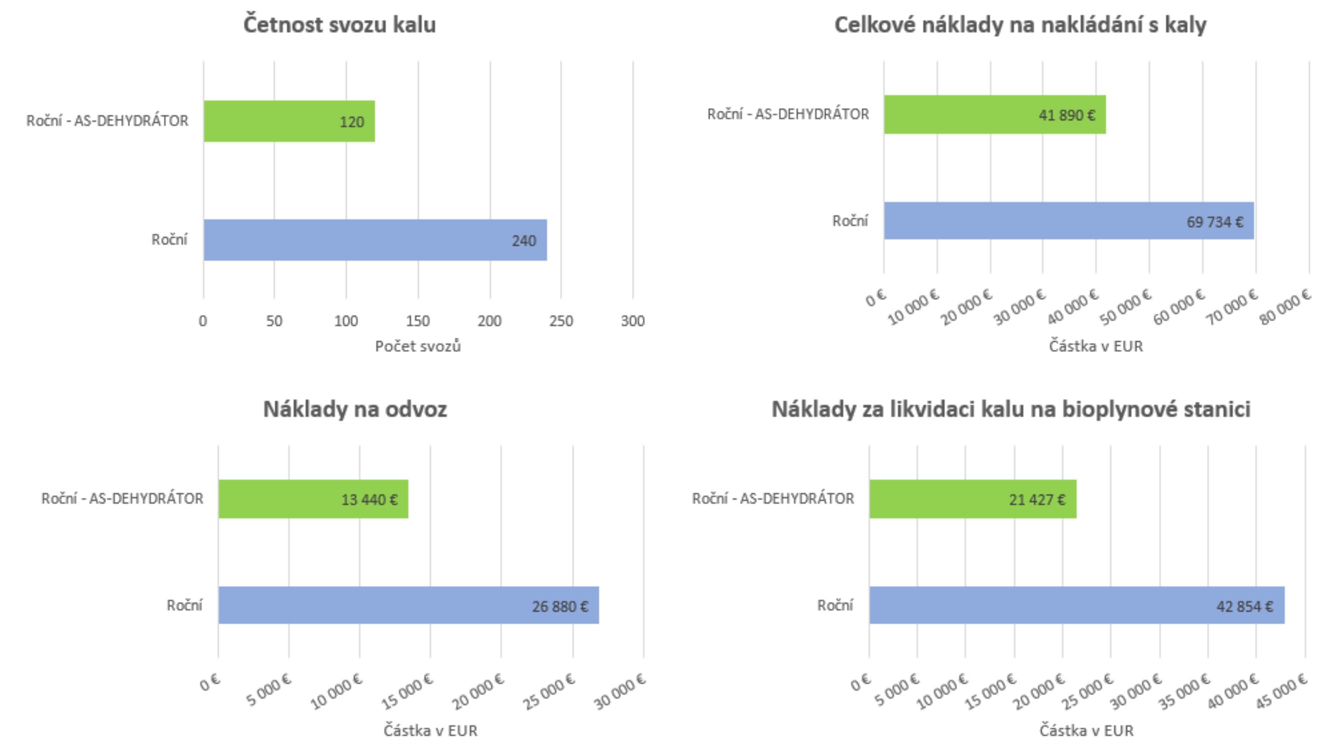
Pilotním testováním bylo zjištěno, že strojní zahuštění kalu je schopné snížit objem kalu přibližně o 50 % a o polovinu tedy snížit četnost vývozů cisternovým vozem. Pokud budeme uvažovat o hodinovém nátoku na zahušťovací jednotku 5 m^3/h, který uvedl investor, tak pracovní režim zahušťovací jednotky bude nastaven na 6 hodin denně 7 dní v týdnu.

Roční provozní náklady na elektrickou energii a spotřebu vody byly vypočítány na 3 444 EUR. Roční náklady na chemii potřebnou k předúpravě kalu byly vypočítány na 3 579 EUR ročně. Četnost vývozů se sníží na polovinu. Dle informací o ceně za jeden vývoz to činí 13 440 EUR. Sníží se objem kalů, které se likvidují na bioplynové stanici. Dle informací o ceně za likvidaci kalů na bioplynové stanici to činí 21 427 EUR ročně. Nákladová cena, kterou investor platí za likvidaci kalu na bioplynové stanici je za příjem kalu, který na bioplynovou stanici odveze. Konečné náklady za roční provoz strojního zahuštění kalů se zahušťovací jednotkou AS-DEHYDRÁTOR činí 41 890 EUR.

Původní náklady činily 69 734 EUR ročně za odvoz pouze gravitačně zahuštěného kalu na bioplynovou stanici [5]. Instalací zahušťovací jednotky se ušetří ročně 27 844 EUR. Roční náklady na nakládání s kaly se tedy sníží o 40 %. Do nákladů na roční provoz zařízení AS-DEHYDRÁTOR jsou započítány náklady za elektrickou energii k provozu zařízení, náklady za spotřebu vody potřebnou k ostřiku lamel a náklady na chemii potřebnou k předúpravě kalu.

V rámci zahušťovací jednotky je vyžadován servis – výměna lamel a šnekovnice z nerezové oceli po 10 000 – 15 000 motohodinách. V uvažovaném pracovním režimu zahušťovací jednotky bude výměna servisních dílů probíhat po 5 – 7 letech provozu.

Zařízení je na ČOV Milsy a.s. nainstalováno trvale a byl již úspěšně ukončen zkušební provoz.



Obrázek 3: Grafické porovnání nákladů za likvidaci gravitačně zahuštěného kalu a strojově zahuštěného kalu

Závěry

Instalací zahušťovací jednotky AS-DEHYDRÁTOR mlékárna ušetří za likvidaci kalu 27 844 EUR ročně, celkové roční náklady se sníží o 40 %. Cena za zahuštění 1 m^3 surového kalu vychází přibližně na 0,64 EUR, při denním zpracování 30 m^3 surového kalu.

Technologie zahušťování kalů představuje zásadní inovaci v oblasti čištění odpadních vod, která přináší nejen ekonomické úspory, ale i významné ekologické benefity. Pilotní testování zařízení AS-DEHYDRÁTOR v mlékárně Milsy a.s. ukázalo, že moderní technologie mohou zásadně optimalizovat nakládání s kalem a snížit celkové náklady na jeho likvidaci až o 40 %. Redukce objemu kalu o polovinu znamená méně časté vývozy cisternovými vozy, nižší spotřebu energie i chemikálií, a především nižší dopad na životní prostředí.

V kontextu průmyslového čištění odpadních vod je právě efektivní manipulace s kalem klíčem k dlouhodobě udržitelnému provozu. Instalace zahušťovacího zařízení umožňuje nejen přímou finanční návratnost, která se v případě mlékárny pohybuje okolo 3,5 roku, ale také flexibilnější nakládání s kalem v budoucnosti, kdy lze očekávat další růst nákladů na odvoz a likvidaci kalových sedimentů.

Technologie AS-DEHYDRÁTOR navíc potvrzuje, že i při relativně nízké energetické náročnosti lze dosáhnout vysoké efektivity separace, přičemž zachovává kontinuitu provozu a nenáročnost na obsluhu. Využití moderních zahušťovacích jednotek se tak jeví jako klíčová strategie nejen pro mlékárenský průmysl, ale i pro další odvětví, kde dochází ke generování přebytečných kalů.

V současnosti, kdy se zvyšují environmentální požadavky a tlak na snižování provozních nákladů, představuje investice do inteligentních zahušťovacích řešení strategické rozhodnutí s dlouhodobým přínosem. Pilotní testování v Milsy a.s. ukazuje, že chytré inovace v oblasti čištění odpadních vod mohou znamenat nejen ekonomickou efektivitu, ale i zodpovědnější přístup k ochraně životního prostředí.

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Results of pilot testing of sludge thickener in the dairy industry

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Summary

This experiment represents one of the approaches to sludge thickening in the dairy industry and presents the results of pilot testing of a new device designed for efficient handling of sludge from treatment processes, not only in the dairy industry.

***Keywords**: Pilot testing, sludge, dairy industry, waste water treatment plant, sludge thickening*

Investigation of the effects of recycled concrete aggregates and emulsified asphalt on the improvement of sandy soil performance

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Abstract

Construction and demolition (C&D) waste significantly contributes to global landfills but has valuable applications in civil engineering. Sandy soils, known for their non-cohesive nature, pose considerable challenges in construction, particularly in embankment and roadbed scenarios. This study examines the impact of Recycled Concrete Aggregates (RCA) and emulsified asphalt on improving the mechanical properties of sandy soils. The results demonstrated that a combination of up to 30% RCA and 25% emulsified asphalt resulted in notable improvements in compressive strength and elastic modulus, achieving average values of 360 kPa and 2.4 MPa, respectively. However, excessive RCA content adversely affects the material's effectiveness. Notably, increased proportions of both additives greatly improved the modulus of elasticity, indicating enhanced resistance to deformation. The binding properties of emulsified asphalt contributed to better cohesion among sand particles, thereby strengthening structural integrity. Conversely, higher RCA percentages were associated with a decrease in fracture energy, raising concerns about material stability and resilience. Overall, the integration of emulsified asphalt and RCA is shown to significantly enhance the mechanical characteristics of sandy soil, making it a viable solution for construction challenges involving non-cohesive soils.

***Keywords:** Waste, utilization of recycled materials, recycled concrete aggregates, emulsified asphalt, soil stabilization*

Introduction

The production and extensive use of construction materials, along with the resulting environmental pollution, represent a global challenge. However, the incorporation of recycled materials in infrastructure projects and their reuse serves as a viable solution to mitigate environmental damage, thereby reducing the reliance on new materials in human life and civil infrastructure. Furthermore, suitable soil and substrates for infrastructural development are increasingly scarce due to inadequate physical and mechanical properties. The presence of quicksand in desert and coastal regions poses significant challenges for the construction of pavements and roads. Quicksand, characterized by its loose, water-saturated sand, can undermine structural integrity, leading to unexpected sinkholes and instability[1]. Moreover, its unpredictable behavior complicates the engineering processes, necessitating specialized techniques and materials for effective stabilization. The high variability in moisture content further exacerbates these issues, requiring constant monitoring and maintenance. As a result, projects in these regions often face delays and increased costs, emphasizing the need for thorough geotechnical assessments and innovative engineering solutions to mitigate risks associated with quicksand[2]. The costs associated with the relocation and improvement of sandy soils, commonly found along coastlines and desert regions, are substantial. The advancement of innovative technologies for utilizing loose and sandy soils by enhancing and increasing their strength has always been a focal point for researchers. The application of polymeric materials, particularly emulsified asphalts, has garnered attention as well. These polymers, derived from crude oil and recognized as asphalt, serve as binding and penetrating agents for materials and soil particles. The surface coating of silica aggregates in sandy areas along coastlines and deserts is notably illustrated in Figure 1.

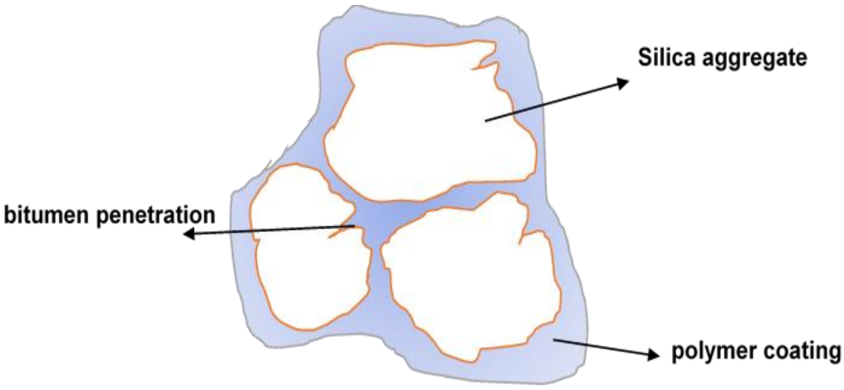

Figure 1: Connection of petrochemical polymers and emulsified asphalt to aggregates

As illustrated in Figure 1, the polymer coating on aggregates enhances their adhesion, thereby ensuring their stability and impermeability. This coating significantly reduces the absorption of water by soil particles, which contributes to the overall mechanical strength and load-bearing capacity of the soil. The use of emulsified asphalt-stabilized sandy soils diminishes the occurrence of rutting and surface deformations in roads and construction sites. Researchers in chemistry and civil engineering have previously focused on weak subsoils treated with binding agents such as cement and lime; the chemical bonds formed by lime and cement sufficiently bind soil particles together[3]. However, a major concern arises from the greenhouse gas emissions, particularly CO_2, associated with the excessive use of these binding agents. Estimates indicate that in 2001, around 16.1 tons of limestone and 4 tons of dolomite were consumed in the United States, leading to the release of approximately 9 tons of carbon dioxide (equating to 2.4 tons of carbon) into the atmosphere[4]. This accounted for 1.7% of the greenhouse gas emissions and 0.13% of total emissions in the U.S. for that year. Industrialized countries face substantial waste challenges, including fly ash, stone dust, plastics, glass, rubber, and construction debris, with ceramic materials, especially crushed concrete and its derivatives, representing the largest volume in the construction industry. Globally, the production of crushed concrete is increasing rapidly, particularly in Iran, Turkey, and China. However, approximately 250,000 tons remain unused annually, while 100 million tons of concrete are utilized for repairs worldwide[5]. Construction and demolition (C&D) waste constitutes a significant portion of landfilled waste globally; nevertheless, these materials have been successfully utilized in various civil engineering applications such as road construction, embankments, drainage pipes, and fill materials. In Australia, for instance, about 8.7 million tons of recycled concrete aggregates, 1.3 million tons of crushed brick, and 1.2 million tons of recycled asphalt are produced annually. Managing this vast quantity of C&D waste poses challenges for urban areas worldwide[6]. Utilizing recycled C&D materials in construction projects presents a sustainable and cost-effective solution, aiding in waste reduction, conserving natural resources, and lowering construction costs. Through further research and innovation, new and beneficial applications for C&D materials in civil engineering can be explored, leveraging their environmental and economic advantages. In Table 1, the advantages and disadvantages of using crushed concrete materials are summarized.

Researchers have demonstrated that the application of emulsified asphalt on sandy soil using a direct shear device leads to an increase in the shear strength parameters C and φ of the sandy soil. Additionally, a study has shown that the mechanical properties of sand, when combined with both cement and polymer, result in a decrease in soil density[9]. Notably, even with an increase in cement content, the dry density remains unchanged. Furthermore, the unconfined compressive strength layer, California Bearing Ratio (CBR), and deviator stress of the stabilized soil sample are found to increase[10]. The impact of adding emulsified asphalt and rubber crumbs to sandy soils has also been investigated using an oedometer, revealing a reduction in permeability, Young's modulus, and internal friction angle, while the volumetric compression coefficient and static soil pressure increase[11].

Table 1: Characteristics, benefits, and drawbacks of crushed concrete aggregate[7,8]

Mechanical and physical properties	Drawbacks	Benefits and useful experiences
• High water absorption • High initial strength • Low abrasiveness • Potential weakness against impact • Presence of varying sizes and gradation	• Non-uniformity of raw materials • Long-term durability concerns • High volume • Risk of corrosion and degradation	1. Application in soil stabilization and gradation improvement 2. Use as a substitute for natural aggregates 3. Good stability in environmental and moisture conditions 4. Reduction in costs and negative environmental impacts 5. Filling capacity for areas requiring backfill

The objective of stabilizing subgrade soils in road construction, landscaping, and the development of parking lots is to enhance the strength and uniformity of both coarse and fine soils. This stabilization process ensures effective transfer of loads from upper layers to weaker sublayers. This study explores the simultaneous use of recycled crushed concrete from demolished or under-construction buildings, which alters the gradation of the soil. Additionally, the concurrent application of emulsified asphalt contributes to the flexibility of the substructure and subgrade in both road construction and residential complex landscaping.

Experimental part

In this study, windblown desert sand from the outskirts of arid urban areas was collected to determine its particle size distribution and physical quality. As depicted in Fig. 2, the particle size analysis was conducted, and the addition of recycled concrete aggregate with specified sizes and varying percentages modified the grading of this soil. Following the AASHTO soil classification method, this material falls into the SP category, characterized by uniformly graded and relatively fine sand, which is often rated low in terms of its application for landscaping layers and subgrade construction. The sand was extracted from a depth of 0.5 meters beneath the surface. The recycled concrete used in this study originated from remnants of broken samples created in the civil engineering laboratory by researchers. To obtain suitable sizes, the sandy aggregates were initially crushed with a hammer, resulting in particle sizes ranging between 4.75 mm (#4) and 0.425 mm (#40). Since the samples were sourced from laboratory concrete mixtures, they contained no additional impurities and were simply crushed and sieved. To eliminate any potential dust and clay particles, the material was washed with water, soaked for 24 hours, and then dried for four hours at a temperature of 105^{o}C. Finer particles below the #200 sieve (0.075mm) were completely removed, while larger sizes were not used due to the difficulty of mixing and the tendency of sand particles to depend on coarser RCA aggregates rather than interlocking. Additionally, particles finer than 0.075 mm were discarded due to the potential for excessive and unregulated impurities. The fines, often regarded as the most challenging aspect of recycled materials, play a crucial role in determining the overall quality and viability of such materials in real-world applications. By analyzing these finer fractions in a manner that mimics on-site conditions, researchers can obtain results that are far more reflective of the actual characteristics encountered in construction projects. This approach would not only align with practical constraints faced during the separation of aggregates in execution projects—where the feasibility of isolating finer material is limited — but also broaden our understanding of how these materials behave under operational conditions.

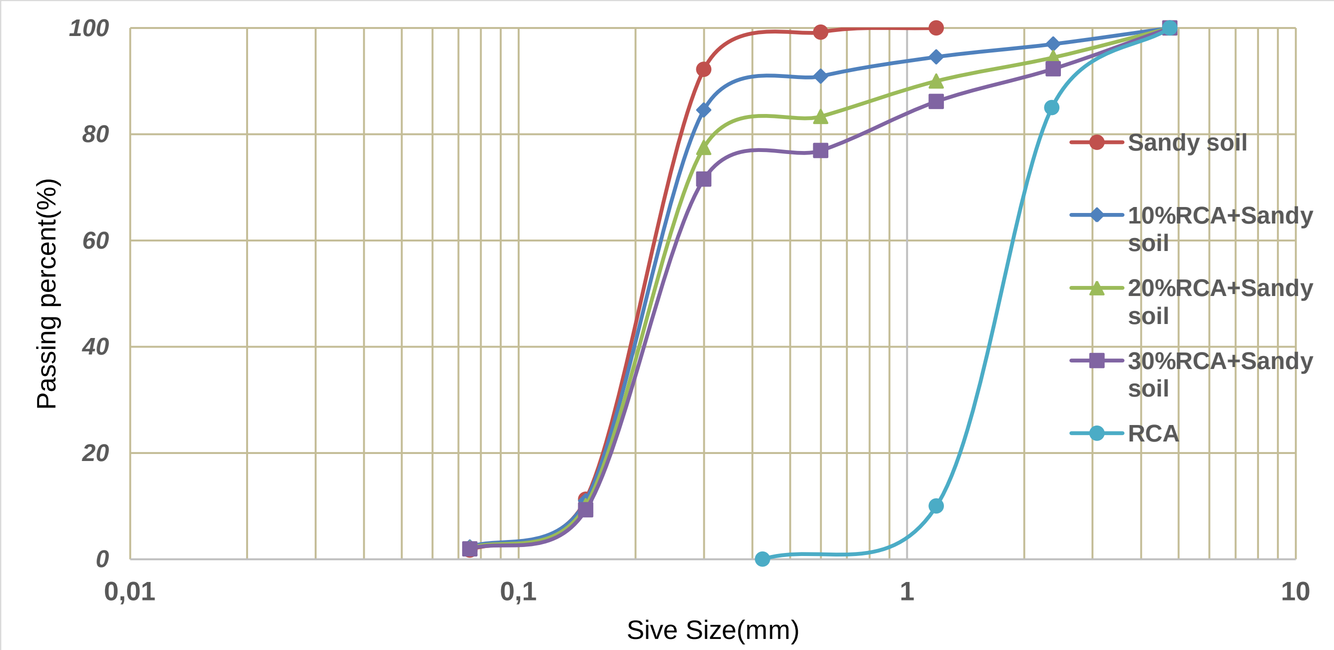

***Figure 2:* Gradation of the base sandy soil and the gradation after the addition of recycled concrete**

The conceptual model of the research process is illustrated in Fig.3, where the strategy of reducing energy consumption and raw material resources is aligned with minimizing the accumulation of construction waste materials. This approach is utilized to stabilize weak substrates in building and road construction. In laboratory testing and sample preparation, emulsified asphalt was considered the primary stabilizing agent, while recycled concrete waste served to enhance soil resistance properties. Laboratory samples were created with varying percentages of recycled concrete waste (10%, 20%, and 30%) and emulsified asphalt (20%, 22.5%, and 25%). The mixing methodology involved blending the soil with the optimal water content (12.5%) before incorporating various emulsified asphalt percentages and subsequently adding the recycled concrete waste. Considering the fine aggregate utilized and its specific surface area, coupled with the incorporation of recycled aggregate as an additive, it was deemed advantageous to employ higher percentages of emulsified asphalt. Preliminary tests indicated that lower percentages of asphalt did not provide the requisite adhesion. The use of Recycled Concrete Aggregate (RCA), in particular, is indicative of a strategic approach aimed at mitigating the environmental burden associated with construction waste. By opting for RCA, we not only aim to repurpose materials that would typically contribute to landfill accumulation but also enhance the sustainability of construction practices. From a scientific perspective, the interaction between the emulsified asphalt and the fine aggregates is significantly influenced by their physical and chemical properties. The fine aggregate's larger specific surface area leads to increased asphalt absorption, requiring a higher binder content to achieve optimal bonding. Moreover, the presence of recycled aggregates can alter the physicochemical behavior of the mix due to the potential for increased porosity and variability in surface texture. This necessitates a careful balance in the formulation to ensure adequate adhesion and performance of the final product. The effectiveness of emulsified asphalt in forming a homogenous matrix can be attributed to its ability to encapsulate the finer aggregates, thereby reducing interparticle voids and enhancing cohesion, which is vital for the mechanical integrity of the composite material.

Once the homogeneity of the mixture was confirmed, the prepared samples were compacted within molds and layered accordingly. Cylindrical soil samples with a diameter of 5 cm and a height of 7.5 cm were employed for the unconfined compressive strength testing. These dimensions were selected to ensure consistency across all experimental trials and to facilitate comparability of results. The size of the samples aligns with standard practices in geotechnical standard test, providing meaningful insights into the mechanical behavior of sandy soils treated with RCA and emulsified asphalt. Thirty soil samples with varying RCA and emulsified asphalt proportions were analyzed to optimize sandy soil performance and stability.

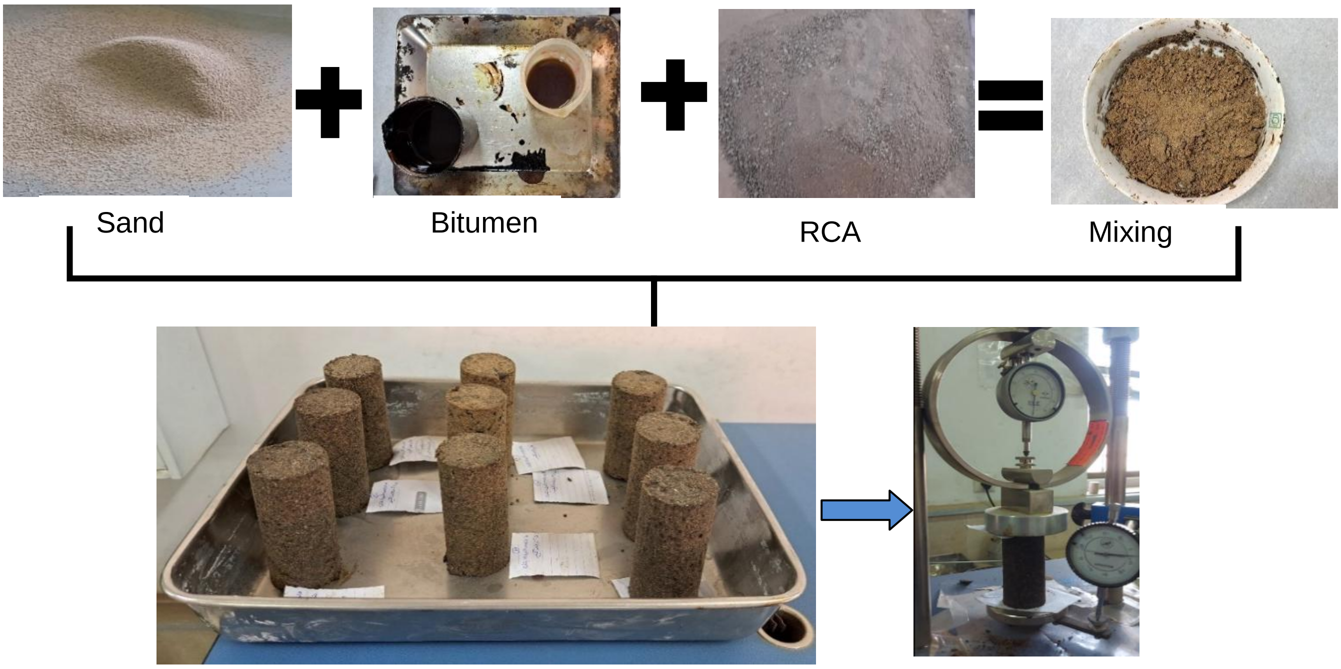

Figure 3: Connection of petrochemical polymers and emulsified asphalt to aggregates

The experimental design included tests for unconfined compressive strength, ultimate load, and strain at failure, as well as the E_{50} modulus and energy at which cylindrical soil samples failed. Following the analysis of results through response surface methodology, an optimal composition of materials and emulsified asphalt RCA was determined. The coding method for the samples was SCxEy, where x represents the percentage of RCA and y indicates the percentage of emulsified asphalt present in the sample. The emulsified asphalt must provide a minimum complete coverage for the mineral particles of the soil, and it is crucial that this coverage is both comprehensive and durable. Therefore, the mixing of soil particles with emulsified asphalt is vital for the quality of stabilization, and the viscosity of the emulsified asphalt used plays a significant role in the performance of the mixture. Numerous studies have reported varying percentages of emulsified asphalt added to soil, ranging from 4% to 25%[12]. The addition of emulsified asphalt initially increases the soil's bulk density, which is later followed by a reduction in bulk density, while also enhancing the optimal moisture content of the soil in both laboratory and field compaction tests.

Results and discussion

Uniaxial compressive strength

The uniaxial compressive strength (q_u) test demonstrated observable stress-strain variations as shown in Fig. 4, following the loading of the samples (an example of stress-strain graph). The samples utilized for examining the uniaxial compressive strength of sand containing recycled concrete aggregate (RCA) and emulsified asphalt clearly indicate that an increase in the percentage of RCA results in enhanced compressive strength. This phenomenon may be attributed to the superior strength of the recycled aggregates, which replace fine sand particles that are naturally rounded. Additionally, the results indicate that as the percentage of emulsified asphalt increases, the compressive strength also rises. This improvement may be due to enhanced adhesion between the sand particles and the reclaimed concrete debris. On average, the increase in compressive strength corresponds to an additional increase of 3% for each percentage of RCA added. Previous studies have also confirmed that a higher percentage of RCA contributes to the increased compressive strength of stabilized soil[9].

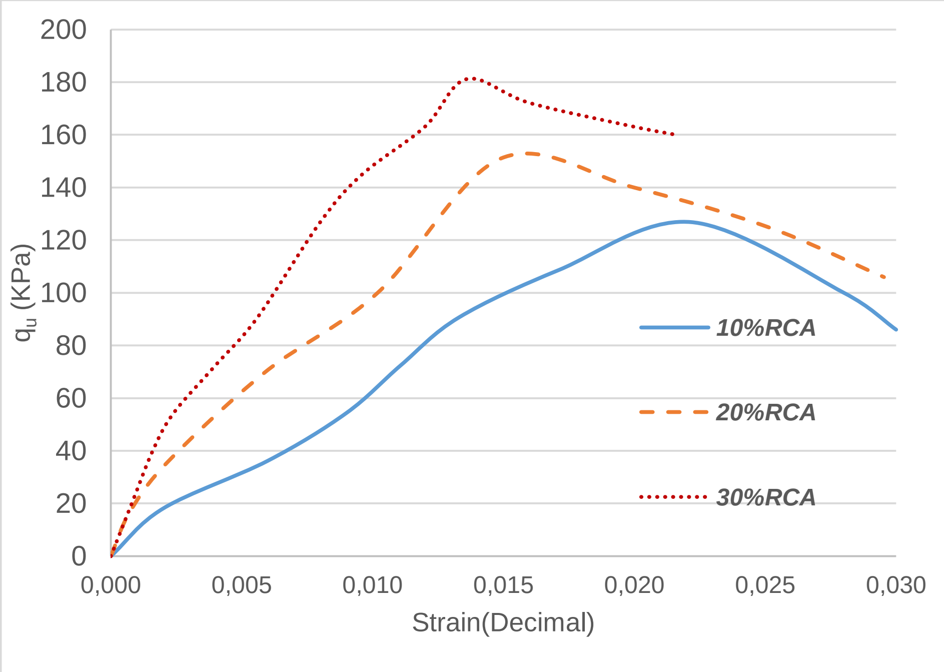

Figure 4: Uniaxial test results of soil stabilized with 20% emulsion bitumen and different percentages of concrete waste

Based on the results presented in the previous figures, it is evident that compacted sandy soils containing RCA and Sand exhibit an increase in emulsion asphalt percentages, whereas an excessive increase in sand can lead to a reduction in strength. The decline in strength due to the rise in sandy soil may be attributed to the adhesive nature of the polymer and the particles constituting the sandy soil, with an overabundance of these materials around the particles potentially increasing the friction between them, thereby resulting in diminished strength. Uniaxial stress increases with higher percentages of emulsion asphalt, accompanied by a corresponding increase in strain, indicative of the brittle behavior of the samples. Although the stress-strain curves are quite similar, there is a notable difference in the maximum uniaxial stress and strain at failure. As the percentage of RCA increases, the strain at failure decreases, which suggests that samples containing higher RCA demonstrate less brittle behavior compared to those with lower emulsion asphalt percentages. Table 2 presents the values of maximum uniaxial stress and strain at the moment of failure (strain at failure) for the stabilized samples.

Table 2: Maximum uniaxial stress and strain at failure for stabilized samples

Sample composition (Mass percentage)		Maximum uniaxial stress (kPa)	Strain at failure (%)
Emulsion Asphalt (%)	**Recycled Concrete (%)**		
20.0	10	126.8	2.2
	20	151.1	1.5
	30	181.1	1.4
22.5	10	181.0	1.5
	20	226.5	1.3
	30	285.4	1.2
25.0	10	246.4	1.5
	20	291.7	1.4
	30	362.4	1.2

The polymeric nature of the emulsion asphalt can result in added friction among particles when excessive RS is present, which may lead to increased resistance to movement, thereby compromising the overall structural integrity of the mixture. This phenomenon aligns with studies on particle friction and cohesion in geotechnical engineering. Notably, while uniaxial stress increases with emulsion asphalt, samples enriched with RCA demonstrate a reduction in strain at failure, suggesting a transition toward more ductile behavior with higher RCA content. This attenuation of brittleness indicates a complex interplay between the types of recycled aggregates used and their mechanical performance in saturated sandy soils[13].

The data indicates that mixtures containing 20% emulsified asphalt and 10% recycled concrete (RCA) exhibited the highest strain at failure of 2.2%, which suggests a remarkable ductility and resilience in comparison to other formulations, where the strain at failure was comparatively lower, remaining around 1.3% to 1.5%. This phenomenon can be attributed to the unique rheological properties of emulsified asphalt, which possesses a viscoelastic nature, allowing for reversible deformation up to a certain threshold. The interplay between the adhesive characteristics of the asphalt and the aggregate matrix contributes significantly to the composite's overall performance. As the asphalt content increases, the interaction between asphalt and RCA fosters enhanced cohesion and internal friction, thus increasing the maximum uniaxial stress while simultaneously influencing the strain behavior under load. This behavior can be interpreted through the lens of solid mechanics, where the emulsified asphalt matrix serves not only as a binder that imparts lubrication but also as a medium that dissipates energy during deformation, particularly upon reaching failure. As the composition shifts towards higher percentages of asphalt, a critical threshold is observed, beyond which the material's capacity to deform elastically diminishes, resulting in reduced strain values at failure. According to Table 2, the maximum compressive stress observed is 360 kPa. This increase can be mechanically and physically justified by the interaction between the emulsion asphalt and the RCA particles. The emulsion improves adhesion and cohesion within the matrix, reducing microstructural defects and enhancing load transfer efficiency. Simultaneously, the angularity and rough surface texture of RCA contribute to interlocking mechanisms, improving stress distribution and overall resistance.

Elastic modulus

The elastic modulus, denoted by E, represents the slope of the linear portion of the stress-strain curve for soil. This value indicates how resistant the soil is to deformation. When this slope is calculated at the beginning of the curve, it is referred to as the initial elastic modulus (E_0). However, since this curve is typically not linear, the tangent or secant modulus known as E_{50} is employed instead. To calculate E_{50}, a line is drawn from the origin to the point representing 50% of the ultimate strength, and the slope of this line is considered the secant elastic modulus. The elastic modulus of soil can be determined through laboratory, field, and empirical methods[14]. In laboratory methods, tests such as consolidation, unconfined compressive strength, direct shear, and triaxial compressive strength are used to compute this parameter. Additionally, field tests including field loading, pressuremeter, and dilatometer tests are applied for this purpose. In this research, the results from unconfined compressive strength tests were utilized to determine the secant elastic modulus of stabilized soil. Fig. 5 displays the specifications of the elastic modulus for various percentages of emulsified asphalt and recycled concrete. Regarding the elastic modulus, the maximum value occurs at the specified percentage, as illustrated in Figure 5. This phenomenon can be explained based on material science and solid mechanics principles. The optimal RCA-emulsion ratio leads to a balanced microstructure, where the improved interfacial bonding minimizes voids and microcracks while maintaining sufficient stiffness. This results in an efficient load-bearing capacity without excessive brittleness, thereby achieving the highest modulus at this composition.

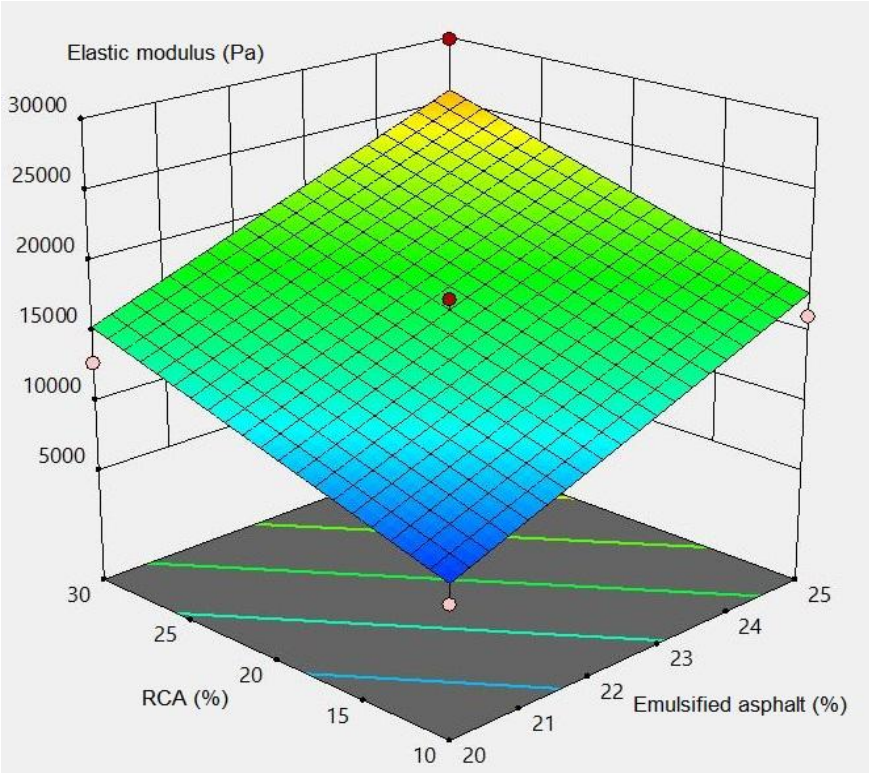

Figure 5: Elastic modulus specifications for stabilized samples

In tests conducted on samples of sand stabilized with emulsified asphalt and recycled concrete, it was observed that an increase in the proportion of emulsified asphalt and recycled concrete in the mixture significantly raised the modulus of elasticity of the samples. This indicates that the addition of emulsified asphalt and recycled concrete improves the mechanical properties of sandy soil, particularly its resistance to deformation. In other words, as the quantity of stabilizing materials increases, the sandy soil exhibits a stiffer behavior and undergoes less deformation under applied loads. As the moisture content increases, the sandy soil exhibits a stiffer behavior and experiences less deformation under applied loads. Research by various scholars has similarly identified enhancements in the mechanical behavior of soil mixtures that include different additives, such as asphalt emulsions and recycled materials. Their findings demonstrate not only increased stiffness but also improvements in other mechanical properties like shear strength and load-bearing capacity[15]. Additionally, researchers have explored the effectiveness of using recycled concrete aggregates in soil stabilization, revealing that their incorporation significantly enhances the overall structural performance of soil mixtures under simulated loading conditions[16]. In the context of the investigation into the effects of Recycled Concrete Aggregates (RCA) and emulsified asphalt on the performance of sandy soils, it is crucial to delve into the interplay between internal friction angles, particle size distribution, and the addition of asphalt as a binding agent. The findings of laboratory tests indicate a positive correlation between the increasing proportions of RCA and the enhancement of both unconfined compressive strength and the elastic modulus of sandy soil mixtures. This improvement can be attributed to the angularity and interlocking ability of RCA, which augments the internal friction angle, thereby providing greater resistance to shear stresses. However, as RCA content exceeds optimal thresholds, a detrimental impact on material resilience is observed, likely due to the fragmentation and altered particle distribution, which can lead to reduced cohesion and increased susceptibility to failure under dynamic loading conditions. Furthermore, the incorporation of emulsified asphalt not only facilitates improved particle binding and cohesion among the sandy matrix but also modifies the gradation characteristics, resulting in a more favorable particle size distribution that enhances the overall mechanical performance. The mechanical and physical behaviors underlying these modifications emphasize the importance of careful consideration of RCA proportions, as excessive amounts can compromise the structural integrity despite the initial benefits observed with moderate inclusion rates.

Energy of fracture

The energy of fracture serves as a pivotal metric in the comprehensive analysis of the fracture behavior of various materials, fundamentally influenced by the applied stress and the corresponding material response. This parameter is crucial as it reflects the inherent resistance of materials to cracking and eventual failure, which are essential considerations in structural applications. The energy required for the failure of a stabilized mixture, for instance, is contingent upon its load-bearing capacity and the extent of displacement it endures under stress. Empirical findings garnered from medium-temperature fracture tests reveal a significant trend: as the percentage of Recycled Concrete Aggregate (RCA) incorporated into the stabilized mixture increases, there is a corresponding rise in the maximum force demanded for the failure of asphalt mixtures. This observation highlights a complex interplay wherein an escalation in RCA content is associated with a higher force requirement for fracture, while simultaneously, the displacement observed diminishes. This dynamic suggests that the increased force cannot adequately offset the reduction in displacement, a relationship that underscores the intricate balance between these two parameters. As depicted in Fig. 6, the energy of fracture experiences a decline with higher RCA percentages, indicating a potential compromise in stability and resilience of the material. Moreover, the inclusion of emulsified asphalt proves to alter the mechanical properties of the stabilized sand mixture, enhancing its pliability, which in turn increases the energy of fracture. This enhancement not only suggests an improvement in material performance under stress but is also observable in similar clay materials treated with emulsified asphalt, reaffirming the significance of additive interactions in modifying the fracture mechanics of composite materials.

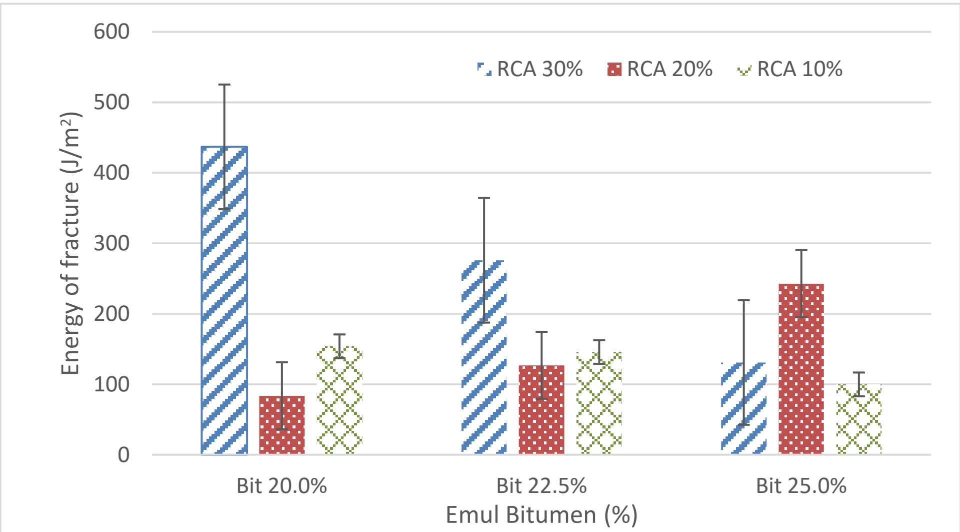

Figure 6: Effects of emulsion percentages and RCA variability on energy fracture

Fracture mechanism and crack propagation

Emulsified asphalt enhances the cohesion between soil particles and fills the interstitial spaces, thereby improving the tensile and shear strength of the soil while preventing crack propagation. Higher-viscosity, more adhesive emulsified asphalts typically result in a reduction of the crack angle. Recycled concrete serves as a reinforcing network within the soil, enhancing its tensile and shear strength and impeding the spread of cracks. The characteristics of concrete particles within the soil, including their size, shape, and distribution, play a significant role in determining the angle of cracks. To analyze the fracture mechanism and crack propagation during uniaxial compressive resistance testing, several methods can be utilized. These include direct observation of the failure surface post-fracture and measuring the crack angle through techniques such as direct measurement or image analysis. One of the most significant effects of soil stabilization with emulsified asphalt and recycled concrete is the reduction of the internal friction angle, consequently leading to a decrease in the crack angle. This indicates that as the amount of stabilizing materials increases, the soil becomes more robust and exhibits less propensity for high-angle cracking. Stabilization leads to a more uniform distribution of cracks within the sample, preventing the formation of large and sudden cracks. Figure 7 illustrates an example of crack propagation following uniaxial testing.

Figure 7: The propagation of cracks in the sample post-failure

It can be concluded that increasing the percentages of emulsified asphalt and recycled concrete also results in reduced crack angles. Fig. 8, demonstrates the decrease in crack angles with the increasing percentages of emulsified asphalt and RCA.

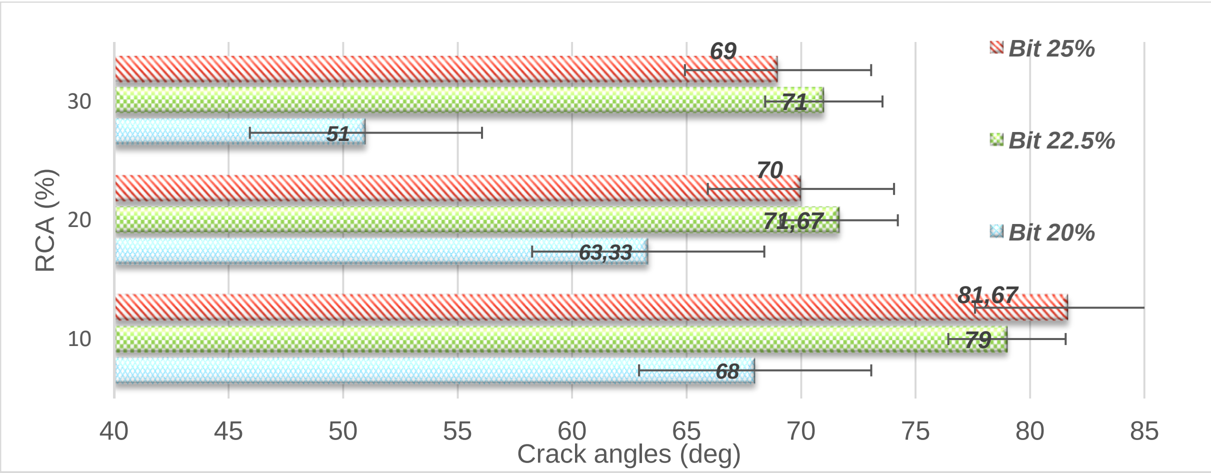

Figure 8: Crack angles of stabilized samples

This paper examines the advantageous outcomes of these resources and contrasts results from recent academic publications that emphasize their influence on stabilization efficacy. Emulsified asphalt, known for its binding properties, enhances the cohesion among sand particles, leading to improved structural integrity. The introduction of recycled concrete aggregates (RCA) further bolsters this effect RCA not only enhances binding capacity but also reduces waste generated from construction activities, thereby supporting sustainability. Research conducted by scholars shows that using emulsified asphalt together with RCA for soil stabilization leads to a significant reduction in cracking — an indicator of improved stability — compared to conventional stabilization methods. Their study reveals a linear correlation where increasing the percentage of emulsified asphalt combined with RCA consistently results in tighter crack angles, thereby improving the material's resistance to environmental stresses[17]. Research indicates that emulsified asphalt, when enhanced with 12% by weight of processed rubber powder, yields an effective emulsion and improves storage stability. Exceeding this concentration leads to uneven distribution, negatively impacting the integrity of the mixture. Notably, the 12% rubber powder dosage significantly enhances the residual strength of evaporated asphalt, thereby improving its performance at high temperatures, which is crucial for the durability of pavements. The use of rubber powder in road construction underscores its role as an environmentally friendly solution for tire disposal, while simultaneously contributing to sustainable road infrastructure[18]. In previous studies, the fracture properties of Cement Emulsified Asphalt Mortar at service temperature were examined under mixed-mode I & II fracture conditions. Experiments using Semi-Circular Bending (SCB) specimens evaluated the mixed-mode fracture energy, with the volume fractions of mortar constituents considered as independent variables. A D-Optimal mixture design was utilized to optimize the experimental approach, leading to the development of a regression model that correlates fracture energy with mortar components. The optimal mix design for maximizing fracture energy was identified, revealing that both cement and asphalt significantly impacted energy variations. Higher asphalt emulsion-to-cement ratios were found to decrease the maximum load capacity while increasing deformation[19]. Results indicated that as the emulsified asphalt content increased, the crack angles showed a corresponding reduction. The authors assert that the reduction in crack angles not only enhances the durability of wind-sand structures but also prolongs the lifecycle of pavement built in such environments. This phenomenon can be explained by examining the underlying mechanisms that influence stress distribution within the stabilized composite material. The application of emulsified asphalt fosters the development of a cohesive network that interlocks effectively with surrounding sand particles. When external stresses are applied to the pavement, the elastic properties of the asphalt facilitate energy dissipation and redistribution throughout the material. This process significantly reduces the likelihood of crack initiation at acute angles, which are known to be critical points of vulnerability in pavement structures. Furthermore, the incorporation of recycled concrete aggregate (RCA) into the mix enhances this system by providing a rougher surface texture that improves particle interlock. The increased interfacial friction between the aggregates promotes effective load distribution, thus mitigating stress concentration points that typically lead to the formation of cracks. These combined effects result in a more resilient pavement structure, capable of withstanding the harsh environmental conditions often encountered in wind-sand environments. Ultimately, understanding the interplay between emulsified asphalt and RCA in influencing crack angle reduction offers valuable insights into the engineering design of sustainable and durable infrastructural components in challenging terrains.

Interaction mechanism between soil, bitumen, and RCA

The behavior of sandy soils can be described through various soil mechanics relationships, including the Mohr-Coulomb failure criterion[20] (as relation 1):

$$\tau = C + \sigma \times \tan(\emptyset) \qquad (1)$$

- τ = shear strength of the soil
- c_c = cohesion
- σ_σ = normal stress
- ϕ_ϕ = angle of internal friction

The incorporation of bitumen alters both the cohesion c_c and the angle of internal friction ϕ_ϕ by providing a binding mechanism at the particle interfaces. The result is a composite material with enhanced shear strength, suitable for construction applications such as road subgrades and embankments. When bitumen coats sandy particles, it forms a thin layer that modifies the surface characteristics of the sand. This coating plays a crucial role in increasing the adhesion between particles. The interlocking effect generated by bitumen further increases the frictional resistance. The modified Mohr-Coulomb failure criterion (as relation 2) can be applied here as well:

$$\tau = C_{Bit} + \sigma \times \tan(\emptyset_{RCA}) \qquad (2)$$

where: C_{Bit} and $\emptyset_{RCA}$ are the cohesion and angle of internal friction for the bitumen-modified RCA.

The binding mechanism primarily works through the reduction of moisture penetration and the alteration of surface properties, which enhances inter-particle friction. Incorporating recycled concrete aggregates into construction and civil engineering applications presents an opportunity to promote sustainability within the industry. However, RCA often exhibits a higher porosity and weaker inter-particle bonding compared to natural aggregates. The interaction of bitumen with RCA can significantly enhance its mechanical properties. Bitumen coats the surface of RCA, similar to its interaction with sandy particles, leading to improved adhesion between aggregates. Notably, the similarities in results across the other mixtures suggest that the mechanical responses are influenced by the intrinsic behaviors of the materials involved. Understanding the rheological properties of the emulsified asphalt, as well as its reversible and elastic behavior upon failure, is paramount when assessing the solid mechanics and physical behavior of sandy soils stabilized with emulsified asphalt. The relationship described by the

Mohr-Coulomb failure criterion (Relation 1) provides a foundational framework for analyzing shear strength dynamics, which are indeed modified through the incorporation of bitumen, as indicated by the subsequent modified criterion (Relation 2). Specifically, the enhancement of both cohesion (C_{Bit}) and the angle of internal friction ($\emptyset_{RCA}$) is attributable to the binding mechanisms at the particle interfaces, which are intensified by the presence of bitumen. This interaction not only reduces moisture penetration but also significantly enhances inter-particle friction, thereby improving the overall mechanical properties of the composite material. It is critical, however, to acknowledge the limitations in accessing triaxial and dynamic triaxial loading equipment for comprehensive investigations. Therefore, it is recommended that future research prioritize further examination of these parameters to validate the obtained results and substantiate the applicability of using sandy soil-modified Emulsion/RCA in field projects, while also demonstrating the practical realism of Relations 1 and 2 through thorough laboratory investigations.

The process of bitumen application results in a composite material exhibiting superior performance characteristics when compared to unmodified RCA. Emulsified bitumen, when combined with fine grains in sand, results in the formation of bituminous mastic as Fig. 9 and what is in the schematic Figure 1, although the overall strength of these mastics may be compromised in specific regions due to variations in composition or application techniques, their utilization in conjunction with recycled concrete aggregates has demonstrated a significant improvement in bond strength. This enhancement is attributed to the compatibility of the mastic with the aggregates, which promotes better adhesion and cohesion, ultimately leading to improved performance in pavement and construction applications. This study demonstrates that incorporating emulsified asphalt and RCA improves soil stability and strength, necessitating precise additive management for optimal results (as Table 3).

Table 3: Benefits and drawbacks of emulsified asphalt and recycled concrete aggregates

Aspect	Benefits	Drawbacks
Compressive Strength	Improved mechanical properties of sandy soils	Excessive RCA contents can compromise stability
Elastic Modulus	Enhanced material performance	Requires careful consideration of additive ratios
Environmental Impact	Promotes sustainability through recycling	Potential variability in material properties
Construction Efficiency	Reduces the need for traditional materials	May require specific handling or application methods

This study emphasizes that the integration of emulsified asphalt and RCA leads to significantly enhanced soil stability, tensile strength, and overall structural performance. However, careful attention must be given to additive proportions to ensure optimal effectiveness.

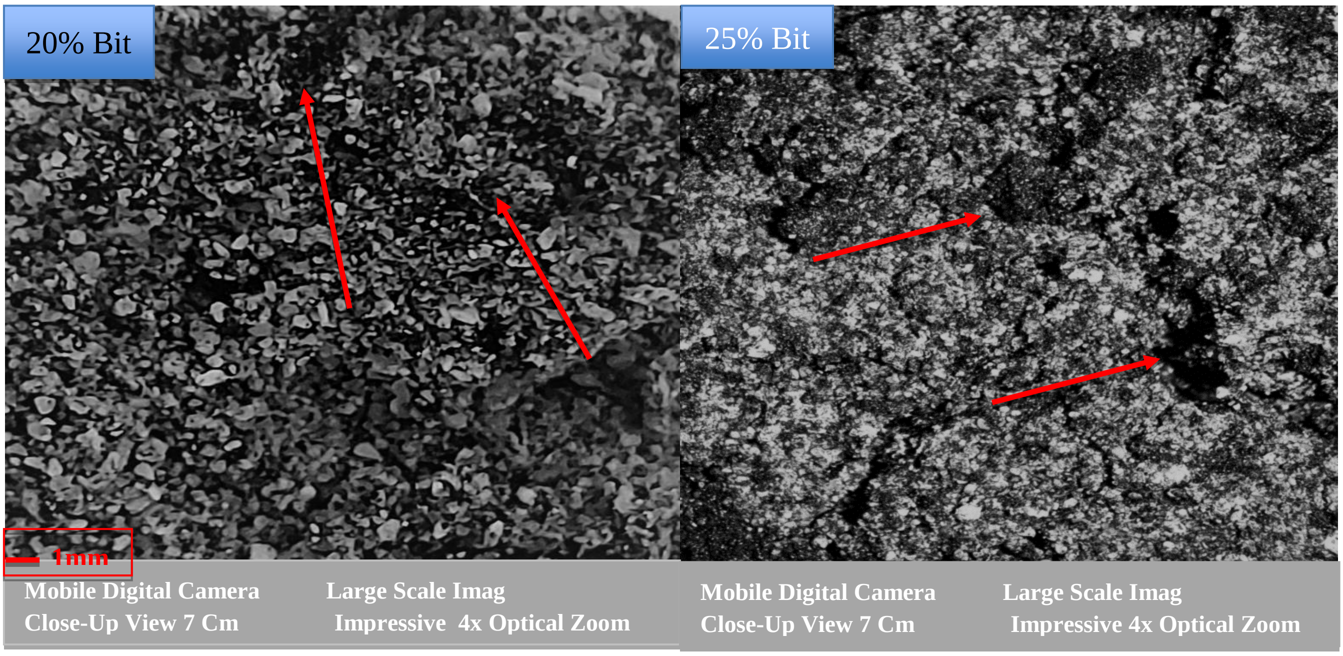

Figure 9: Large-scale image depicting two various concentrations of bitumen emulsion, with arrows indicating the presence of bitumen and fine grain

Conclusions

This investigation highlights the significant potential of utilizing Recycled Concrete Aggregates (RCA) in combination with emulsified asphalt to improve the performance of sandy soils. Given the challenges posed by the non-cohesive nature of these soils in construction applications, the findings suggest that incorporating up to 30% RCA and 25% emulsified asphalt can substantially enhance the mechanical properties, leading to notable increases in both compressive strength and elastic modulus.

- The results indicate that optimal combinations can significantly improve compressive strength and elasticity, providing a promising approach to addressing the inherent challenges posed by non-cohesive soils in construction applications.
- Furthermore, the study reveals that excessive proportions of RCA can compromise material stability, emphasizing the need for careful consideration of additive ratios.
- In conclusion, the study demonstrates that the inclusion of emulsified asphalt and recycled concrete significantly enhances the elastic modulus of sandy soil, leading to improved structural stability.
- The significant impact of emulsified asphalt on enhancing the pliability and energy of fracture in stabilized mixtures emphasizes the importance of additive interactions. Future research should continue to explore these dynamics to optimize material performance in various structural applications, ultimately contributing to more sustainable engineering practices.
- In summary, the incorporation of emulsified asphalt and recycled concrete aggregates significantly enhances soil stability through improved tensile and shear strength, leading to reduced crack angles and a more resilient structural performance.
- The positive correlations drawn from recent research indicate that increasing the percentages of these stabilizing materials yields favorable outcomes in crack propagation and overall material integrity.

The research highlights the effective use of Recycled Concrete Aggregates (RCA) and emulsified asphalt as stabilizers for sandy soils, significantly improving their mechanical properties, including compressive strength and elastic modulus. This approach addresses the challenges posed by non-cohesive soils in construction. Future studies should focus on determining optimal additive ratios to mitigate stability issues from excessive RCA, as well as exploring other binding agents for enhanced material performance, ultimately promoting sustainable practices in civil engineering.

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Vyšetřování účinků recyklovaného betonového kameniva a emulgovaného asfaltu na zlepšení vlastností písčitých půd

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Souhrn

Stavební a demoliční odpady (C&DW) významně přispívají k celosvětovým skládkám, ale mají cenné využití ve stavebním inženýrství. Písčité půdy, známé svou nesoudržnou povahou, představují velké výzvy ve stavebnictví, zejména v případě hrází a podkladů silnic. Tato studie zkoumá vliv recyklovaného betonového kameniva (RCA) a emulgovaného asfaltu na zlepšení mechanických vlastností písčitých půd.

Výsledky ukázaly, že kombinace až 30 % recyklovaného betonového kameniva (RCA) a 25 % emulzního asfaltu vedla k významným zlepšením pevnosti v tlaku a modulu pružnosti, přičemž průměrné hodnoty dosáhly 360 kPa a 2,4 MPa. Avšak nadměrný obsah RCA negativně ovlivňuje účinnost materiálu. Zvýšené podíly obou příměsí výrazně zlepšily modul pružnosti, což svědčí o zvýšené odolnosti proti deformacím. Pojivové vlastnosti emulgovaného asfaltu přispěly k lepší soudržnosti mezi částicemi písku, čímž posílily strukturální integritu. Naopak vyšší podíl RCA byl spojen se snížením lomové energie při porušení, což vyvolává obavy o stabilitu a odolnost materiálu. Celkově se přidání emulgovaného asfaltu a RCA projevilo na významném zlepšení mechanických vlastností písčité půdy, což z ní činí životaschopné řešení stavebních problémů spojených s nesoudržnými půdami.

Klíčová slova: *Stavební a demoliční odpady, využití recyklovaných materiálů, recyklované betonové kamenivo, emulgovaný asfalt, stabilizace půdy*

Study on Dispersivity of Heavy Metals in Undisturbed Soil Columns In and Around Peenya Industrial Area, Bengaluru, India

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Abstract

This paper analyses the effect of heavy metal tracers on the one-dimensional transport of pollutants through the undistributed soil columns done in the laboratory, and experimental data is compared with analytical data. In this study, the advection-dispersion equation is used analytically through 'Mathematica' to evaluate the transport of pollutants. It considers the heavy metal contaminants by considering the input concentrations of pollutants that vary with time and depth. The experiment test results regarding breakthrough curves were analysed, revealing essential patterns in heavy metal migration. The current investigation is to find the dispersion coefficient in and around the industrial area for four heavy metals, i.e., four undisturbed soil columns at station 1(Inside) and four undisturbed soil columns at station 2 (outside). The hydrodynamic dispersion co-efficient 'D' when Chromium (Cr), Nickel (Ni), Zinc (Zn) and Copper (Cu) solution was passed through 20cm soil column (each metal per column)outside industrial area was 3.57 m^2/year, 1.99 m^2/year,10.84 m^2/year, and 3.49 m^2/year and the solution was passed through 20cm soil column(each metal per column) inside industrial area 5.22 m^2/year, 2.2 m^2/year, 8.08 m^2/year, and 6.57 m^2/year. According to the soil column experiment, the lowest mobility is observed in clay soil (Inside the Peenya Industrial Area) rather than in sandy loam soil (outside the Peenya Industrial Area). These findings enhance our understanding of heavy metal pollution and provide a basis for predicting and managing such pollution in industrial areas. The 'Mathematica' used in the present research helps predict the future effects of heavy metal pollution in the study region, thereby equipping us with the knowledge to take proactive measures.

Keywords: *Heavy Metal, Mobility, Undistributed, Breakthrough Curves (BTC), Soil Columns, Peenya Industrial Area (PIA), Groundwater contamination, Hydrodynamic dispersion.*

Introduction

Soil and water are essential resources for life, but human activity is gradually compromising their quality. Urbanisation, industrialisation, and human activities affect water quality. Water contamination threatens ecosystems, long-term ecological stability, human health, and economic development. Emerging water pollutants from various industries contribute significantly to water pollution and directly or indirectly affect water quality, increasing vulnerability to groundwater pollution. Industrial Effluents contain high levels of toxic heavy metals and are the primary source of surface water, groundwater, and soil pollution [1]. Industrial wastewaters are generated through various multidimensional industrial activities. Industrial wastewater can be classified as chemical, electronic, petrochemical, and food processing, containing high BOD (Biochemical Oxygen Demand), COD (Chemical Oxygen Demand), Total solids, TDS (Total Dissolved Solids), TSS (Total Suspended Solids), Inorganic ions, and Non-biodegradable contaminants. Environmental effects from industrial wastewater discharge include improper management of hazardous waste, disposal of heavy metals, and water quality degradation. The pollutants can enter aquifers through various pathways, including leaching, recharge, surface runoff, and leakage, ultimately affecting groundwater quality and posing risks to ecosystems and public health. Gaseous emissions from urban transport systems and industrial exhausts are another primary source of groundwater pollution caused by atmospheric conditions. Groundwater pollution can also arise from air deposition, contaminating soil in urban areas. As contaminants permeate the soil layers and move to groundwater reservoirs, they harm water quality and human health [2,3]. The study aims to identify the major patterns of heavy metal behaviour in soil columns. The study objective is to compare the rigorous laboratory experiments and a comprehensive analysis, providing crucial insights into the transfer of contaminants through undisturbed soil columns. In this study, the advection-dispersion equation is used analytically through 'Mathematica' to evaluate the transport of pollutants, which considers the heavy metal contaminants by considering the input concentrations of pollutants that vary with time and depth.

Heavy metals are elements with relatively high densities (5.3 to 7 g/cm^3) and atomic weight. Even small doses can have serious consequences. Examples of HMs are Mercury (Hg), Cadmium (Cd), Lead (Pb), Chromium (Cr), Arsenic (As), Iron (Fe), Manganese (Mn), Nickel (Ni), Zinc (Zn) & Copper (Cu). They pose health and environmental risks due to their properties, toxicity, nonbiodegradable, and bioaccumulation potential throughout the food chain[1]. Globally, heavy metals in soil and water seriously threaten public health and the environment. Numerous human and natural processes contribute to accumulating these hazardous elements in the environment, which causes pollution. Bioaccumulation means an increase in chemical concentration in a biological organism. Unscientific industrial waste management practices increase heavy metal concentrations, cause metal leaching, and ultimately cause soil and groundwater pollution. Heavy metals can also enter soil from acidic rain and release them into streams, lakes, rivers, and groundwater [4,5].

Soil pollution is caused by both intended and unintended activities, such as on-site industrial pollution, inadequate waste management, mining activities, intentional applications of materials to soil, and atmospheric depositions. Various anthropogenic activities, such as industrialisation, urbanisation, and agricultural practices, lead to the accumulation of pollutants like petroleum products, heavy metals, pesticides, and excessive nutrients in soils. This contamination negatively impacts soil engineering properties, affecting settlement, shear strength, permeability and blocking soil pores. Soil contamination by heavy metals and pesticides also threatens food safety, ecosystems, and public health, necessitating immediate remediation efforts to mitigate harm and ensure sustainability [5,6].

Soils may become contaminated by dumping heavy metal wastes and metalloids through emissions from the rapidly expanding industrial areas, disposal of high metal wastes, leaded gasoline and paints, sewage sludge, pesticides, spillage of petrochemicals, and atmospheric deposition. Problems arise from the leaching of heavy metals from industrial sites. Metal ions are dispersed throughout the environment by water's surface, subsurface, lateral, and vertical motion. Several factors influence heavy metal migration, including soil classification, mineralogy, texture, and leachate composition. It also depends on the season, time, amount of rainfall, temperature, acid rainfall, airborne dust, and other anthropogenic activities.

The transport of industrial chemicals through soils affects groundwater quality [7]. The transport mechanisms of heavy metals through soil have created significant interest to environmental and soil scientists because of the possibility of groundwater contamination through metal leaching. Many soils generally contain heavy metals with varying concentrations depending on the surrounding geological environment, natural and anthropogenic activities [8]. Metal transport is not only dependent on the physiochemical properties of the metals but mainly on the physical and chemical properties of the soil, such as soil organic matter content, clay fraction content, mineralogical composition, and pH, all of which collectively determine the binding ability of soil [9,10].

Hamed Mahdipanah, Askari Tashakori, Samad Emamgholizadeh, and Eisa Maroufpoor [11] conducted a study on the determination of the dispersion coefficient in layered soils. Experiments were performed on homogeneous soil and layered heterogeneous soil with three layers. The present research attempted to determine the effects of parameters on Breakthrough Curve (BTC) and dispersivity values by considering different flow velocities and concentrations, pretending the porous media or aquifers in the layered form, and using mixed methods sampling. The results concluded that the dispersion coefficient for layered heterogeneous soils was 1.96 times less than that of homogeneous soils, indicating the amount of dispersion coefficient in soil changes with the contaminant concentration. Wan Zuhairi W.Y, Abdul Rahim Samsudin, & Nurita Ridwan's [12] study was focused on the Column experiment. It is a very useful apparatus that can be used to study the migration and attenuation of heavy metals through a compacted soil column. This study conducted a column experiment on some natural soils from the Selangor area in Malaysia using different types of heavy metals, namely Cu, Pb, Ni, and Zn. The study has revealed that soils have different capacities to retain heavy metals and very much depend on their physical and chemical properties. The affinity or selectivity of HMs for sorption (or retention) also varies in different types of soils, as proven by the study.

Zhao Wang and Guangyu Lei [13] conducted a study of the Soil column permeability experiments in the laboratory to study the transport characteristics of five heavy metal ions of Mn, Ni, Cd, Cr, and Cu in saturated loess, sandy soil, and compound soil. The results show that the soil texture and the characteristics of heavy metal ions have a common effect on the migration of heavy metal ions. Heavy metal ions in loess do not migrate easily and can be adsorbed on the surface or shallow surface for a long time. It is not easy to cause deeper contamination of groundwater. However, it causes surface runoff to migrate laterally to rivers or other areas and expands the pollution area. The study shows that any type of heavy metal from mining areas with a high content can cause environmental pollution and adverse effects.

Wan Zuhairi W.Y. & Nurita R. [14] performed the soil column study to investigate the retention capability of three soil types in Malaysia, namely marine clay (SBMC), weathered metasediments (HMS) and river alluvium soil (ARA). All soil columns were tested against four types of heavy metals, i.e. copper, lead, nickel, and zinc. The breakthrough curves show that the SBMC has better retention capability on heavy metals than other soils, indicating less migration of heavy metals through the SBMC soil column. The study discovered that heavy metals entered the soil columns and were retained predominantly at the top 30 mm. Mohamed Rashad and Faiz F. Assaad and Elsayed A. Shalaby [15], undertook their study within the soil's plough layer (0-20 cm depth) from two sites near two municipal solid waste dumpsites in Alexandria, Egypt. Column leaching experiments provided valuable information on labile metal pools and the significance of slow reaction kinetics in metal leaching. The results from the study recognised that the cumulative amounts of metal cations released are poorly defined because they can include metal cations released from high-affinity sorption sites on organic matter and oxides.

M.J. Sanchez-Martin, L. F. Lorenzo, and M. Sanchez-Camazano [16] investigated the leaching of Pb, Cd, Zn, and Cu in three representative packed soil columns collected within the zone affected by the spill from a pyrite mine in Aznalcollar (Sevilla, Spain). The study's results discovered that the relative mobilities of the different toxic elements in the columns are Cd> Zn> Cu> Pb. Results also showed that the soils themselves have a good capacity for immobilising the soluble fraction of the elements from the spilt mud. C. M. Niranjan, J. Raji and S.R. Sudheendra [17] investigated the effect of radioactive tracer on the one-dimensional transport of pollutants through the unsaturated porous media and compared it with experimental data. In their study, the advection-dispersion equation is used analytically to evaluate the transport of pollutants, which considers the decay of radioactive contaminants by considering input concentrations of pollutants that vary with time and depth. The solution is obtained with the Laplace transform and moving coordinates to reduce the linear partial differential equation to an ordinary one. Duhamel's theorem is applied using experimental data to receive the complementary error function solution. The outcomes from the research help in the possibilities of applied chemicals leaching through over-irrigation, thereby resulting in groundwater contamination by fertilisers.

Study Area

Peenya Industrial Area (PIA) is the most significant industrial Zone in Bengaluru, Karnataka, India. The Peenya Industrial estate lies in Bengaluru city's north part between latitude 13^0 1’ 42" N and longitude 77^0 30’ 45" E. The Industrial Area is crossed by national highway NH 4, which runs between Bengaluru and Mumbai. It was established in the late 1970s by the KSIDC-Karnataka Small Industrial Development Corporation and has divided the PIA region into 3 Stages. Further, the Karnataka Industrial Development Board has subdivided the 40 km^2 PIA region into four phases: phases 1, 2, 3, and 4 for development and monitoring. BBMP- Bruhat Bangalore Mahanagara Palike will have authority over the

Peenya industrial sector [18]. The PIA comprises about 2,100 types of Industries, including small and medium-scale [19]. Peenya Industrial sector employs around 5,00,000 people. The small and medium-sized industries include pharmaceutical formulations, chemicals industries, polymers industries, leather industries, electroplating industries, lead processing, textile dying, galvanising, degreasing, spray painting, phosphating, pickling industries, anodisation, garment washing, powder coating, plating, and allied industries. Both central and state governments recognise the Peenya Industrial Area (PIA) as the primary hub of Karnataka State's industrial activity and a substantial provider of manufactured goods that are well-regarded for their quality in domestic and international markets. Figure 1. shows the spatial Location map of the study area.

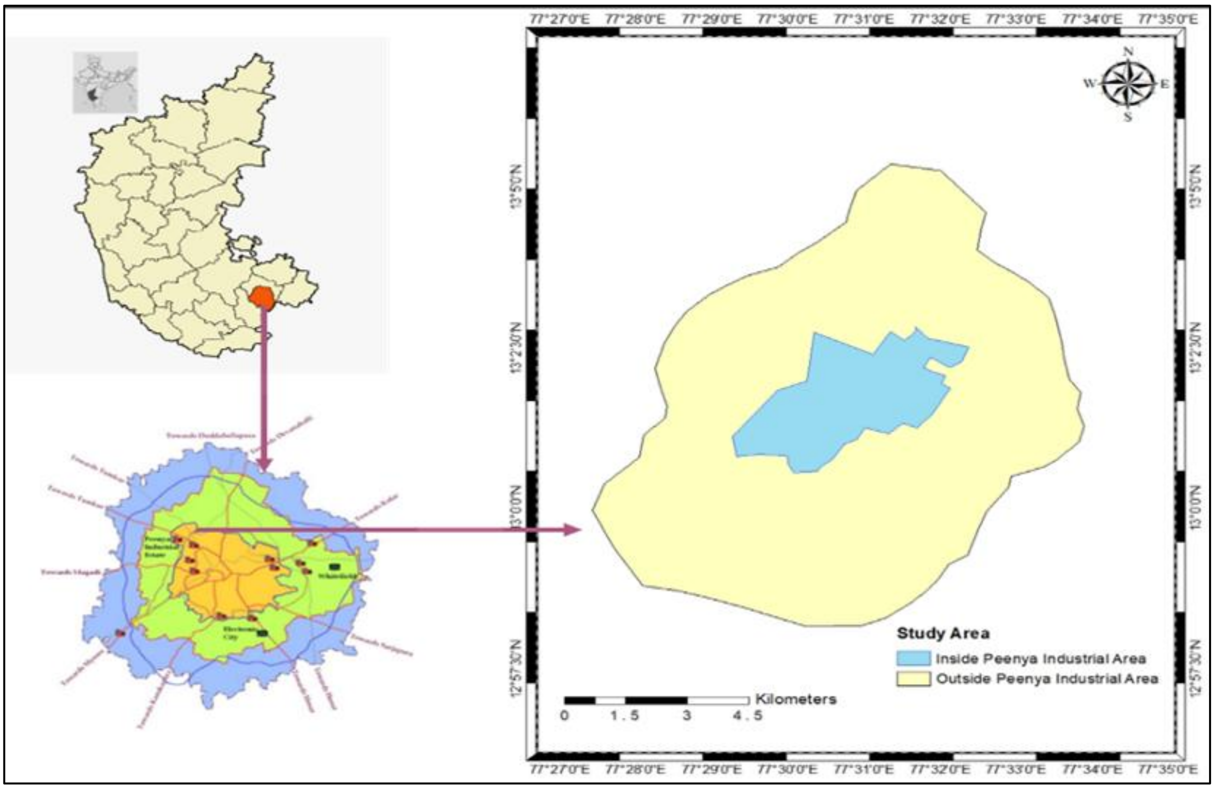

Figure 1: Location Map of Study Area

Topography, Climate and Rainfall

The PIA comes under Bangalore North Taluk and is underlain by banded gneissic complexes and granites of the Archaean age. Both rock types are weathered. The western part of this ridge's drainage flows and joins the Arkavathi, while the eastern plains drain towards the South Pinakini [19]. Over the past 50 years, the research area has received an average of 923 mm of rainfall annually [19]. Most rainfall is received during the southwest monsoon between June and September. September is the wettest month, and January is the driest month. The atmospheric temperature varies between 14° to 34° Celsius. The lowest recorded temperature was 7.8° Celsius, while the highest was 38.9° Celsius. Near the Peenya industrial sector, the Air Quality Index factor varies from satisfactory to moderately polluted.

Hydrogeology, Geology, and Soil

Peninsular gneissic rocks, such as granites, gneisses, and migmatites, are responsible for forming significant aquifers in the metropolitan areas of Bengaluru. The rock, often magmatite, combines igneous and metamorphic rocks [19]. The composite Migmatite rock comprises a metamorphic host material veined or streaked with granite. There are phreatic conditions in the north groundwater of Bengaluru. The weathered zone and the fresh gneisses and granite rock that lie underneath it comprise the whole aquifer system in this region. Depending on the location, the PIA weathering thickness might range from

20 to 24 meters. The groundwater depths before the monsoon season vary from 3.20 meters to 57.38 meters bgl (below ground level), whereas groundwater depths range from 2.50 meters to 37.50 meters bgl after the monsoon season. The soil composition around Bengaluru varies from red loamy to laterite soils. Red sandy soil is typical in the Peenya industrial region. These sandy soils offer good penetration rates, a reasonable water-holding capacity, and a light texture. There are three different types of soils in the research area: sandy clay loamy, sand loamy, and loamy sand. Figure 2. shows the geology map of the study area.

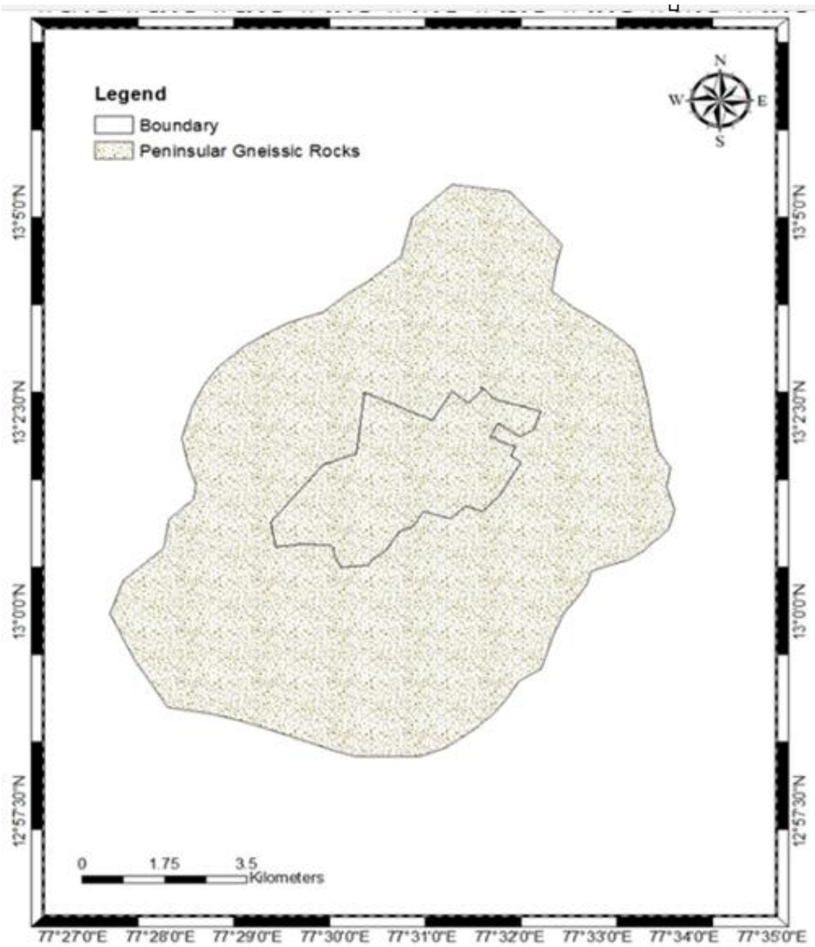

Figure 2: Geology Map of Study Area

Methodology

Soil column studies are a valuable method for investigating the behaviour and movement of heavy metals in soils. Soil column studies provide crucial insights into how heavy metals behave in soil environments and help to develop effective strategies for managing soil contamination and protecting ecosystems. Soil column studies are designed to simulate the natural conditions of soil and its interaction with contaminants, such as heavy metals. The study objectives: 1. To study the major patterns of heavy metal behaviour in soil columns. 2. The Mathematical Software Ttool used in the present research is to help predict future heavy metal pollution in the study region [20,21,22].

Laboratory Tests

Thin-walled steel cylinders are used to construct soil columns. The lower end of the steel pipe was sharpened to reduce compaction inside the column and easily facilitate pipe insertion into the soil. The eight steel cylinders 20cm in height and 10cm in diameter were coated with vegetable oil, inserted at the sampling sites, and collected undisturbed (4 soil samples Inside PIA and another 4 outside PIA). The soil columns are labelled, sealed, and transported in a plastic box to the laboratory. The experimental investigation was carried out on Eight undisturbed soil samples with four different heavy metals. The undistributed soil represents natural conditions. Soil columns are typically constructed in steel cylinders to allow observation of the movement of contaminants. The upper part of the steel column is open, and the outlet hole has evenly meshed at the bottom; a layer of filter paper is laid on the lower ends of the soil column to collect the effluent from the column and to prevent outflux of particles. The soil columns were hung to a steel stand with a hook provided to the stand, as shown in Figure 3.

Methodology for Experimentation

There are two stages of leaching for the column test:

1. Column leaching using deionised water.
2. Column Leaching using a test solution.

The tracer solutions employed were deionised water and aqueous heavy metals solutions. The composition of the aqueous heavy metals test solutions was prepared by dissolving heavy metals in deionised water to obtain a concentration of Chromium: 500 mg/l, Nickel: 560 mg/l, Copper: 400 mg/l, and Zinc: 516 mg/l as this metal were found in higher concentration in the soils tested at same locations during earlier studies conducted for soil [23]. Deionised water having a low pH simulates rainwater percolation through the soil column until all the heavy metals present in the soil are washed out.

Figure 3: Soil Column Experiment

Breakthrough curve (BTC):

The breakthrough curve measures the adsorbate concentration in the fluid phase at the column's exit as a time function. It is a plot of the test duration against the adsorbate concentration in the effluent stream of a liquid with the adsorptive. It is a critical tool for understanding how contaminants migrate and evaluating soil remediation techniques. Breakthrough curves help model and predict the transport and behaviour of contaminants in soil and groundwater systems. Researchers can assess the effectiveness of soil treatments or amendments by comparing breakthrough curves before and after applying remediation techniques. These curves ensure that soil and groundwater contamination levels meet regulatory standards and guidelines. The data obtained from breakthrough curves can guide the design of soil treatment or remediation strategies to manage and mitigate contamination effectively [24, 25].

Application of Mathematica for predicting the transport of heavy metals to groundwater

In recent years, the advection-diffusion equation has drawn considerable attention from hydrologists, civil engineers, mathematical modellers, and environmental scientists researching the migration and characteristics of trace metals in soil. The advection-diffusion equation describes the solute transport caused by the combined effect of diffusion and convection in a medium [11, 17, 26].

Dispersivity is an assessed characteristic in soil porous mediums used to examine the transfer of pollutants to groundwater. Determination of the longitudinal dispersion coefficient in the laboratory is typically done using the analytical solution to the one-dimensional dispersion equation. The solution for the dispersion equation is given by:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial z^2} - u\frac{\partial C}{\partial z}$$

Where *C* is the constituent concentration in the soil, the solution, *t* is the time in minutes, *D* is the hydrodynamic dispersion coefficient, *z* is the depth, and *u* is the average porewater velocity.

Using Fried and Cumbarnous's [27] equation given below and the experimental data about soil columns containing tracer metals, the dispersion coefficient values were calculated:

$$D = \frac{1}{8}\left[\frac{z - vt_{0.16}}{\sqrt{t_{0.16}}} - \frac{z - vt_{0.84}}{\sqrt{t_{0.84}}}\right]^2$$

where $t_{0.16}$ and $t_{0.84}$ are the times required for the concentration ratios of $C/C_0=0.16$ and $C/C_0=0.84$, respectively, to reach a particular distance z.

Metal transport depends not only on the physiochemical characteristics of the metals but also primarily on the physical and chemical characteristics of the soil, including its pH, organic matter content, clay fraction, mineralogical composition, and other factors that define the soil's binding ability [28].

Results and Discussion

The results of soil column experiments using deionised water will illuminate the quantum of metal leached out of the soil. The input to the soil column is drawn from the constant tank containing the tracer and allowed over the column drop by drop. Then, after the soil becomes saturated, the tracer comes out as leachate from the bottom end of the soil column, and the time elapsed is recorded. The collected leachates were subjected to chemical analysis, and breakthrough curves were constructed and discussed in the present section. The soils from the study sites were sampled and subjected to essential physical and chemical tests using standard test procedures.

Table 1 below presents the physical and chemical properties of the soils in the study area. Results show that all the soil samples collected from Inside PIA (Station 1) is clay soil and all soil samples outside (Station 2) the PIA is a sandy loam type.

Table 1: Physical and Chemical results of soil tests

Soil Sample	Latitude	Longitude	pH (1:5)	ECe (dS/m)	CEC (cmol/kg)	OM (%)	OC (%)	sand (%)	silt (%)	clay (%)	Soil structure
Station 1 (Inside PIA)	13.0256417	77.5136416	7.59	0.26	30.43	1.032	0.6	35.56	16.12	48.32	clay soil
Station 2 (Outside PIA)	12.990593	77.491051	6.55	0.08	13.78	1.24	1.17	69.68	18	12.32	sandy loam

CEC (Cation Exchange Capacity): This measures the soil's capacity to attract and hold positively charged ions (cations) like calcium, magnesium, potassium, and sodium, which are essential for plant growth; higher CEC indicates the soil can retain more nutrients.

OM (Organic Matter): This refers to the percentage of decomposed plant and animal material in the soil, which plays a crucial role in improving soil structure, water retention, and nutrient availability.

OC (Organic Carbon): This is a specific component of organic matter, representing the carbon content within the decomposed organic material.

Column leaching using deionised water:

Four undisturbed soil columns inside the Peenya industrial area undergo column leaching separately for 4 tracer elements i.e., First Column for Cr, second column for Ni and likewise using deionised distilled water for nearly 240 hours. At 120 h, the concentration almost becomes zero for Cr and Ni, Zn at 234h (Figure 4a, 4b, 4c), and Cu at 178h (Figure 4d).

Similarly, Column leaching using deionised distilled water takes nearly 240 hours for four undisturbed soil columns outside the PIA. At 120 h, the concentration almost becomes zero for Cr and Ni, Zn at 222h (Figure 5a, 5b, 5c), and Cu at 174h (Figure 5d).

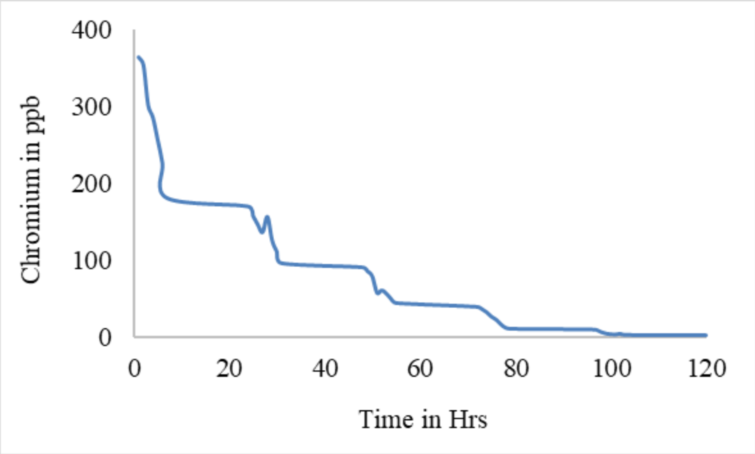

Figure 4a: Deionised water graph of Chromium Inside Peenya Industrial Area (PIA)

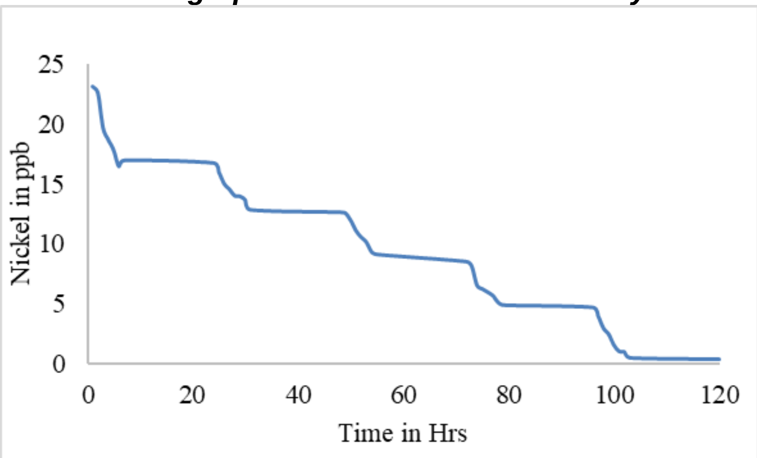

Figure 4b: Deionised water graph of Nickel Inside Peenya Industrial Area (PIA)

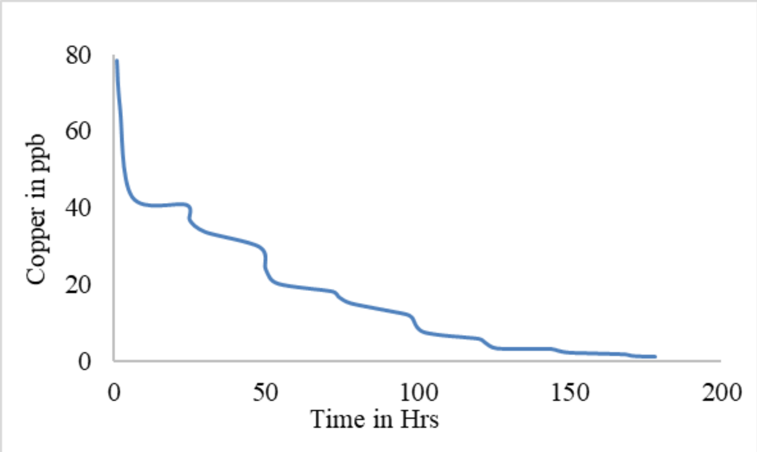

Figure 4c: Deionised water graph of Copper Inside Peenya Industrial Area (PIA)

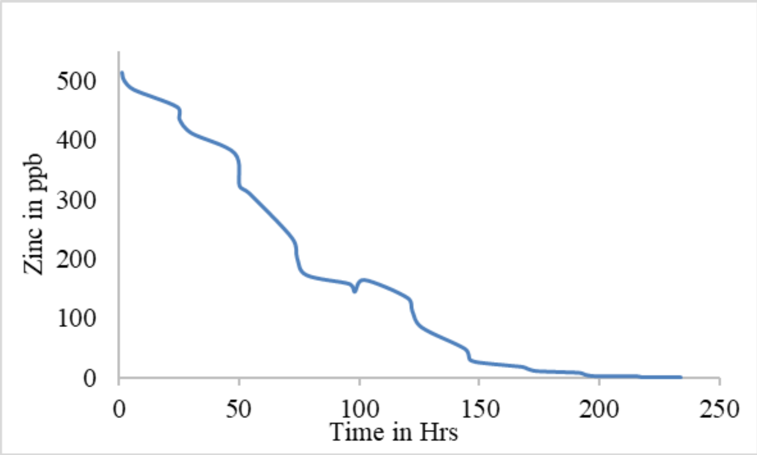

Figure 4d: Deionised water graph of Zinc Inside Peenya Industrial Area (PIA)

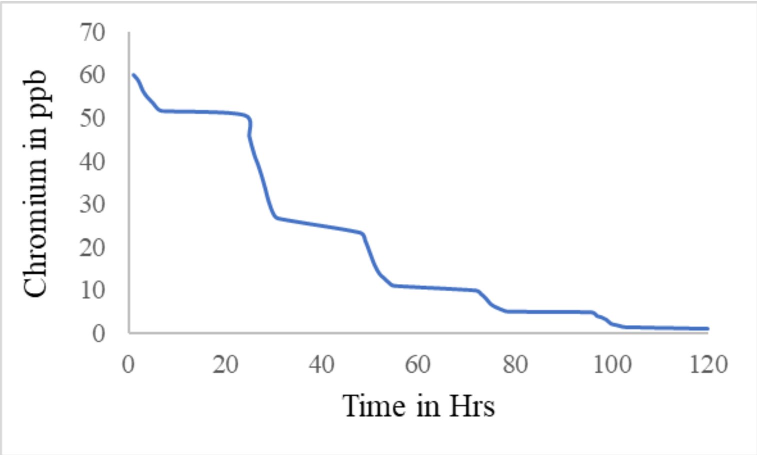

Figure 5a: Deionised water graph of Chromium Outside Peenya Industrial Area (PIA)

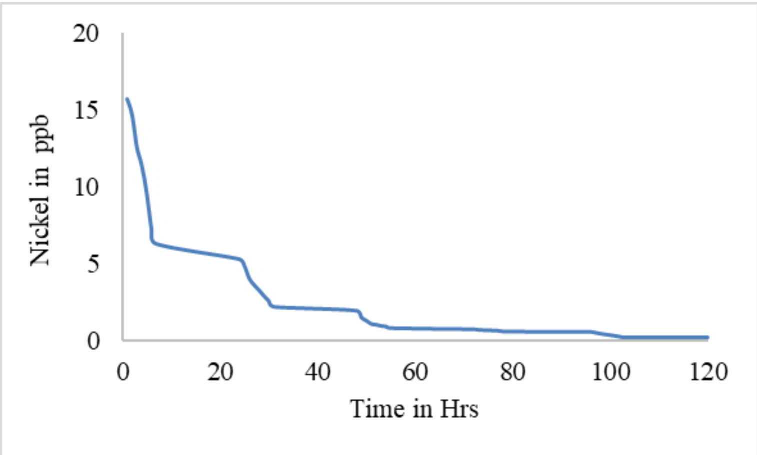

Figure 5b: Deionised water graph of Nickel Outside Peenya Industrial Area (PIA)

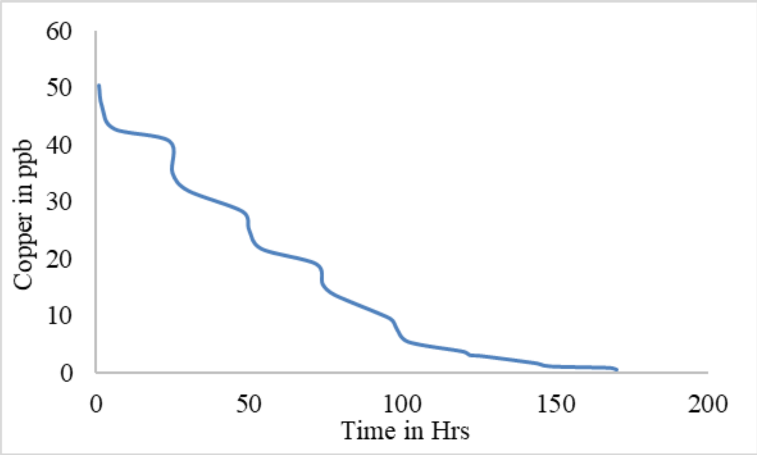

Figure 5c: Deionised water graph of Copper Outside Peenya Industrial Area (PIA)

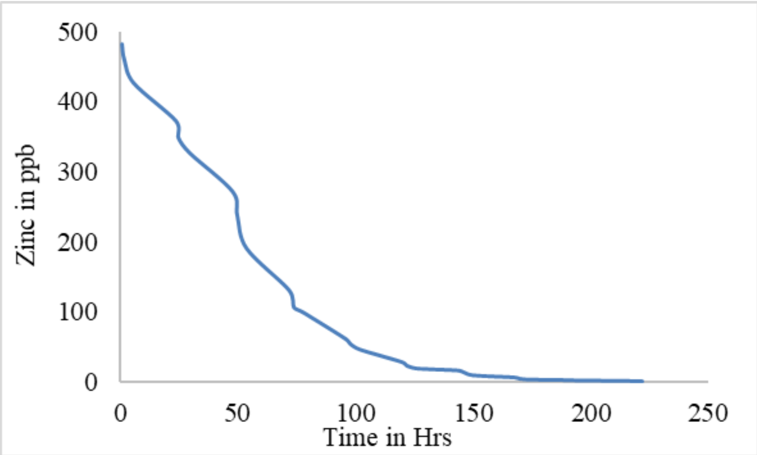

Figure 5d: Deionised water graph of Zinc Outside Peenya Industrial Area (PIA)

Column Leaching using a test solution

Statistical analysis of data and replication of leaching experiments are required to ensure reliability. Synthetic heavy metals solution of Heavy metals of Cr, Ni, Zn and Cu is passed through the unsaturated soil columns collected Inside and Outside the PIA till the soil adsorption capacity is exhausted, and Breakthrough curves (BTC) are plotted. Breakthrough curves are plotted between relative concentration and time. Figures 6(a, b, c, d) and 7(a, b, c, d) show the BTCs of Ni, Cr, Zn and Cu for soils collected inside and outside the PIA.

In summary, the migration processes of four metals in four soils inside the PIA are slower than those outside the PIA. The soil sample collected from inside the PIA is a clay soil type, and the CEC and OM values are high compared to soil collected outside the PIA. The affinity of heavy metals adsorption can be ranked Cu>Zn>Ni>Cr. According to the studies, heavy metal ions are not easier to migrate in clay soil than in sandy soil. The lowest heavy metal mobility is observed in clay soil (inside PIA) compared to sandy loam soil (outside PIA). Because the total surface area for adsorption is slightly higher in clay soil than in sandy loam soil [28,29]. As a result, there is a higher chance of topsoil pollution, and due to surface runoff, it migrates laterally to surface water or other areas and expands the area of pollution. The penetration rates of heavy metals were low at high cation exchange capacity and organic matter. The soil sample collected from inside the PIA is a clay soil type. For the same reason, it is difficult to cause deeper groundwater contamination inside the PIA. However, groundwater pollution exists inside the PIA because of the direct discharge of industrial pollutants into bore wells and improper industrial waste management.

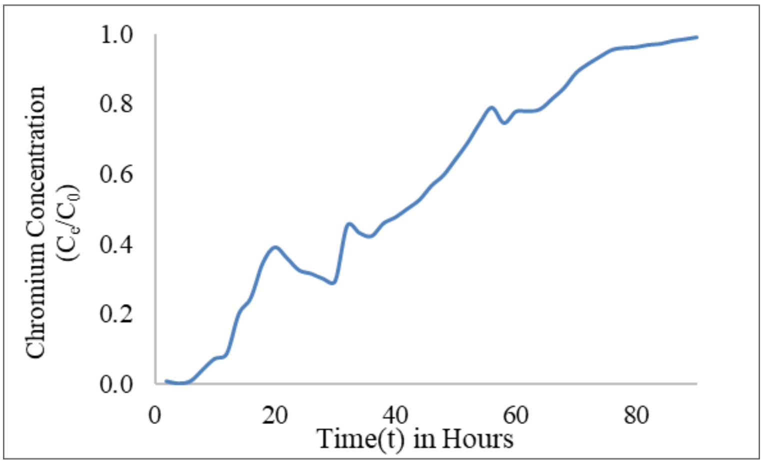

Figure 6a: Break Through Curve of Chromium Inside Peenya Industrial Area (PIA)

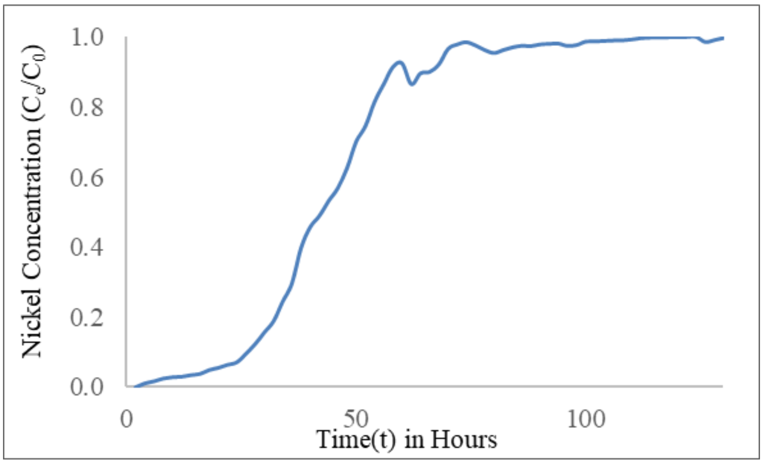

Figure 6b: Break Through Curve of Nickel Inside Peenya Industrial Area (PIA)

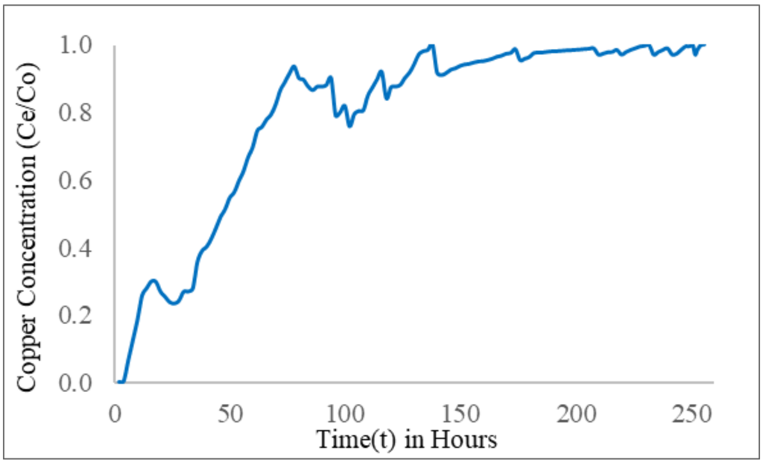

Figure 6c: Break Through Curve of Copper Inside Peenya Industrial Area (PIA)

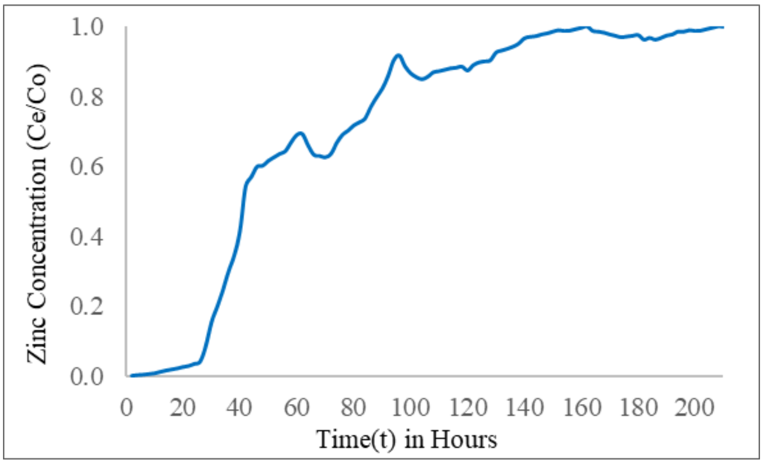

Figure 6d: Break Through Curves Copper Inside Peenya Industrial Area (PIA)

The migration processes of 4 metals in 4 soils outside the PIA differ in the same soil conditions. The soil sample collected from outside the PIA is a sandy loam type of soil and clay soil found inside the industrial area. The mobility of Cr in the soil column is higher than that of other metals in the soil column. The behaviour of Ni percolates from soil samples was very similar to that of Cr. Ce/Co values increased with the number of days. The mobility of Zn is low compared to other metals, such as Cr and Ni, in the soil column. The mobility of Cu in the column is low compared to three metals, Cr, Ni and Zn, in the soil column. The affinity of heavy metals sorption can be ranked Cu>Zn>Ni>Cr. BTCs show retention of heavy metals in the case of Cu and Zn metals and greater mobility in the case of Cr and Ni by soil column. The environmental impact of Heavy Metal contamination strongly depends on the metal specification, mobility, type of soil, and physical and chemical properties of soil. According to the findings, the soil sample taken from outside the Peenya industrial area is a sandy loam soil type. According to studies, heavy metal ions migrate more easily in sandy soil than loess. Also, the CEC and OM values of the sandy loam soil are low. Therefore, the penetration rates of heavy metals were high at low cation exchange capacity and organic matter. This is why metal infiltrates deep into the soil or groundwater and causes pollution.

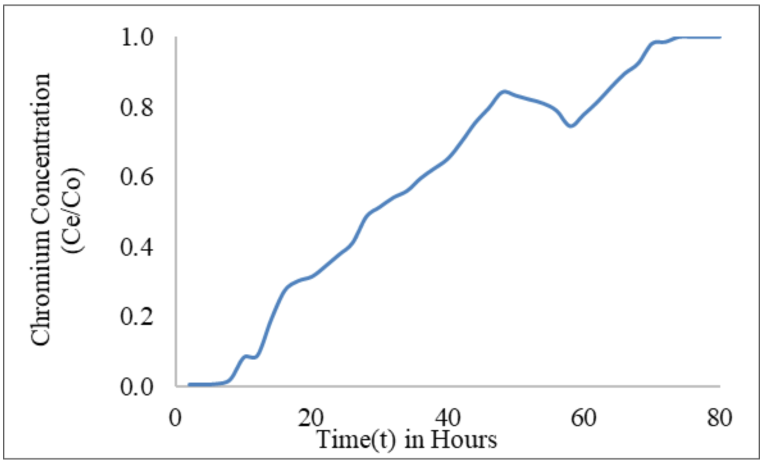

Figure 7a: Break Through Curves Chromium Outside Peenya Industrial Area (PIA)

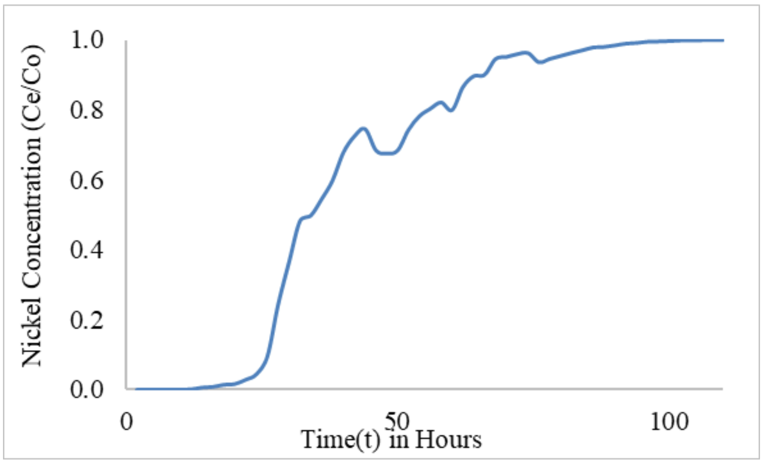

Figure 7b: Break Through Curves Nickel Outside Peenya Industrial Area (PIA)

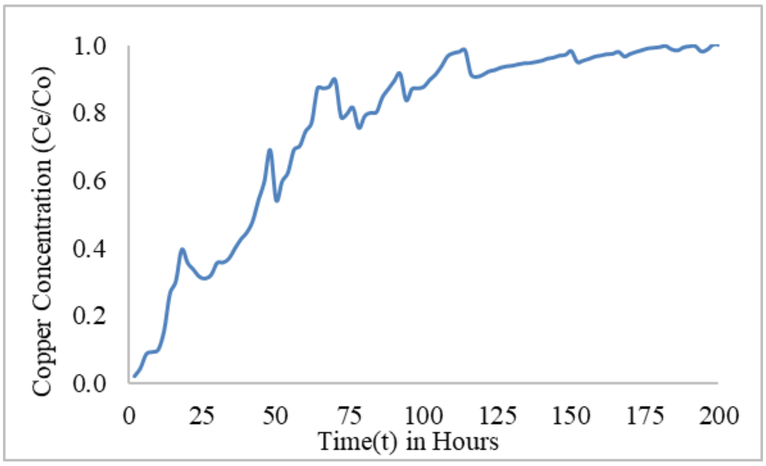

Figure 7c: Break Through Curves Copper Outside Peenya Industrial Area (PIA)

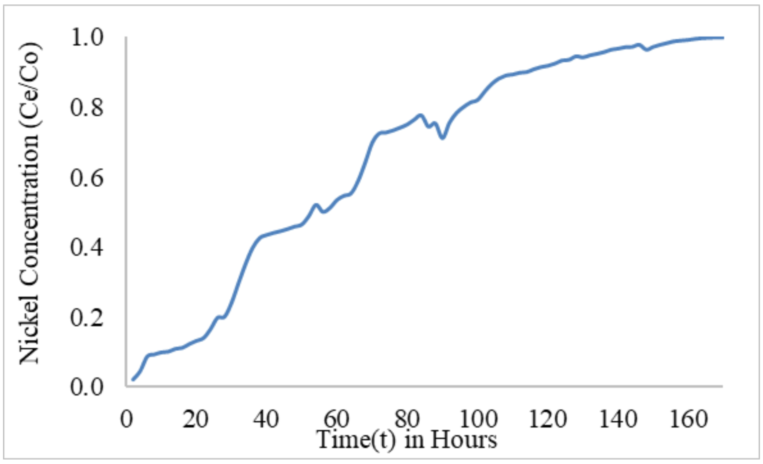

Figure 7d: Breakthrough Curves Zinc Outside Peenya Industrial Area (PIA)

The overall study found that Cr mobility in the soil column is higher than other metals in the soil column in both soils (inside and outside the PIA). Hence, it was proved from the groundwater analysis that Cr concentrations are higher than the standards found in the borewells inside and around the PIA. The penetration time of all metals in sandy loam soil (outside the PIA) is less than that in clay soil (inside the PIA). The study revealed that soils have different capacities to retain heavy metals and depend on their physical and chemical properties.

Water-containing contaminants, like sewage and industrial wastes, seep into the soil matrix from direct flow from overland regions due to runoff. Eventually, the aquifer, a groundwater storage basin, receives this water. It is a source of potable water. Water moves through the soil, mixing, dispersing, and diffusing the contaminants in the flowing flux. The development of more precise and cost-effective models for forecasting the transport and destiny of solutes, frequently from solute sources in the unsaturated soil zone, resulted from this. Fried and Cumbarnous's equation calculated the hydrodynamic dispersion coefficient when the heavy metal solution was passed through a 20 cm soil column, as shown in Table 2. The transport of dissolved contaminates is an essential process in groundwater hydrology. Predicting solute concentrations and illustrating the effects of different transport parameters are usually accomplished by one-dimensional analytical solutions of the governing equations. The application of mathematical models application software like `Mathematica' to predict the transport of heavy metals to groundwater plays a vital role in the study [17]. From the one-dimensional dispersion equation, $C/C_0$ was numerically computed using `Mathematica'.

Table 2: Dispersion coefficient values

Study Site	Parameter	D ($m^2\ yr^{-1}$)	$t_{0.16}$ (hr)	$t_{0.84}$ (hr)
Station 1 (Inside Peenya Industrial Area)	Chromium Tracer	5.22	15	54
	Nickel Tracer	2.2	25	104
	Zinc Tracer	8.08	20	178
	Copper Tracer	6.57	16	226
Station 2 (Outside Peenya Industrial Area)	Chromium Tracer	3.57	14	56
	Nickel Tracer	1.99	24	86
	Zinc Tracer	10.84	14	136
	Copper Tracer	3.49	22	186

D= Dispersion Coefficient, $t_{0.16}$ and $t_{0.84}$ are the times required for the concentration.

The comparison values between experimental and calculated values are represented for the Inside PIA and Outside PIA, respectively. Figures represent the break-through curves for C_e/C_0 vs time for 20cm depth. It is seen that the concentration field increases in the beginning and reaches a steady state value for a fixed depth. The composition of the theory and experiment breaks through curves. Figures 8(a, b, c & d) and 9 (a, b, c & d) compare calculated values with the experimental ones and are found to align well for both Inside and Outside PIA, respectively. Both the curves Mathematica and BTC are close to each other. Hence, it is possible to use the models based on the observed physical conditions to predict a dimensional flow pattern when experimentations can be avoided altogether [17].

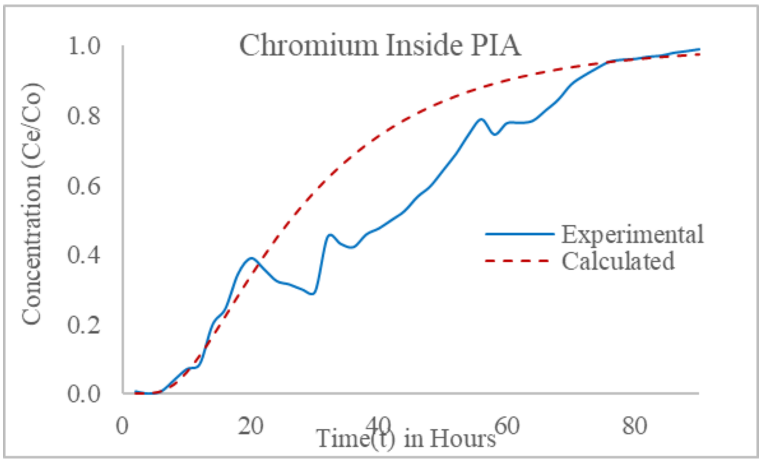

Figure 8a: Breakthrough Curve of Experimental Vs Calculated Chromium Inside Peenya Industrial Area (PIA)

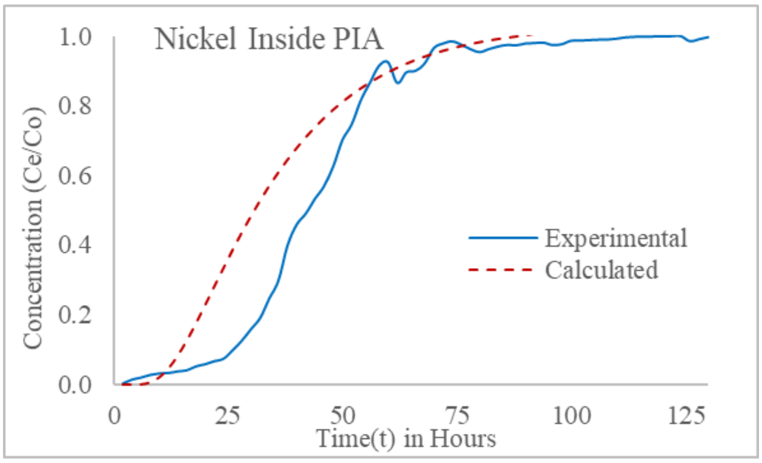

Figure 8b: Breakthrough Curve of Experimental Vs Calculated Nickel Inside Peenya Industrial Area (PIA)

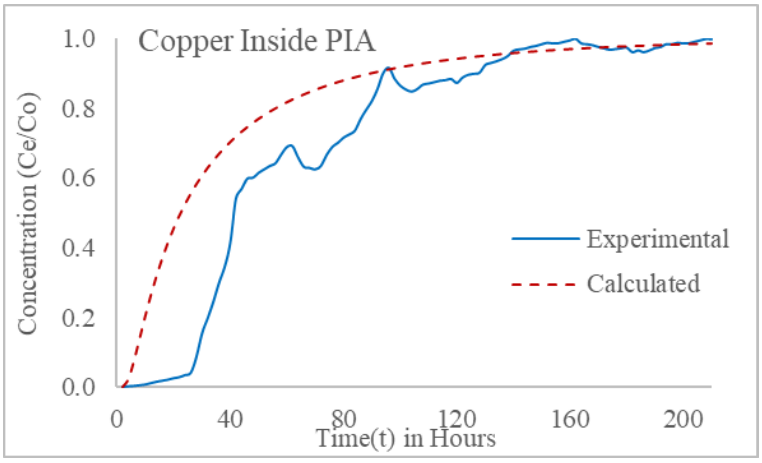

Figure 8c: Breakthrough Curve of Experimental Vs Calculated Copper Inside Peenya Industrial Area (PIA)

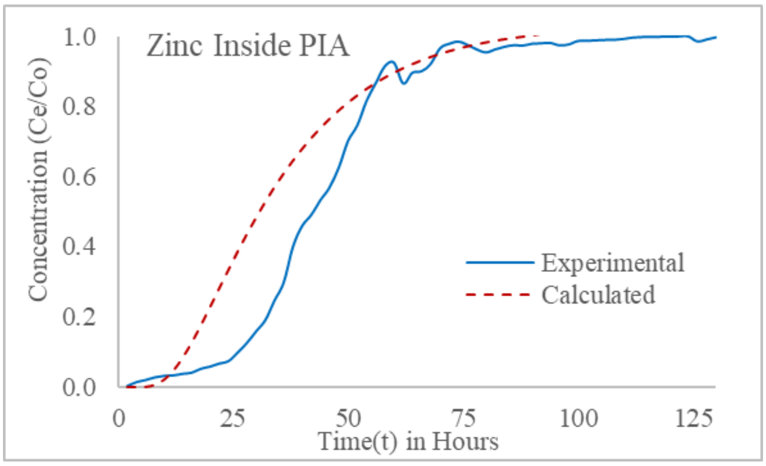

Figure 8d: Breakthrough Curve of Experimental Vs Calculated Zinc Inside Peenya Industrial Area (PIA)

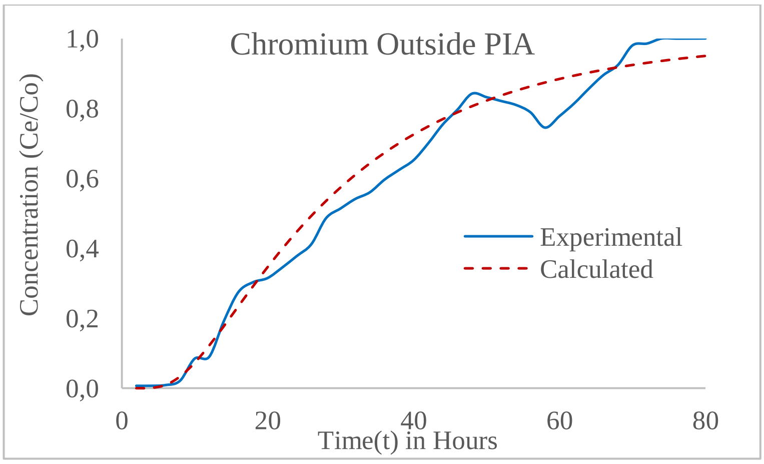

Figure 9a: Breakthrough Curve of Experimental Vs Calculated Chromium Outside Peenya Industrial Area (PIA)

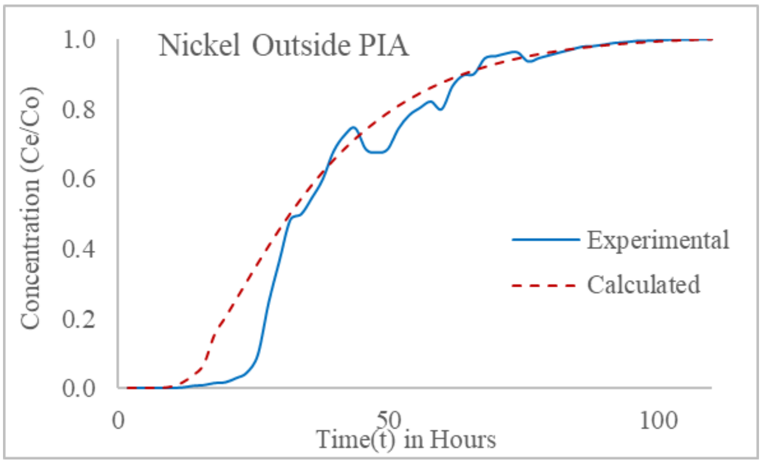

Figure 9b: Breakthrough Curve of Experimental Vs Calculated Nickel Outside Peenya Industrial Area (PIA)

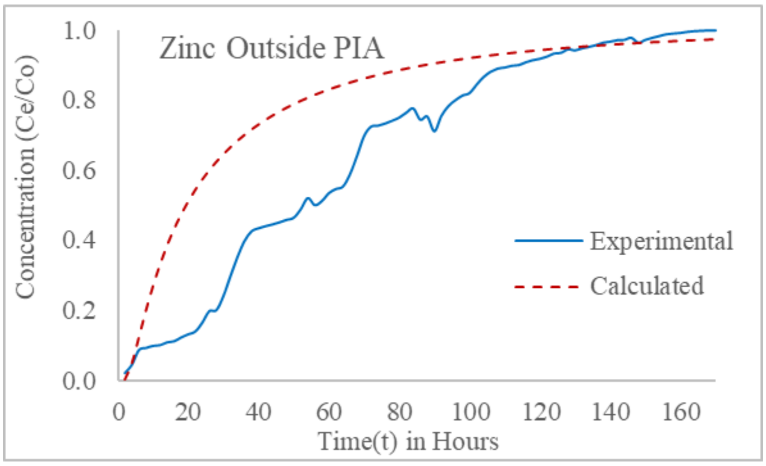

Figure 9c: Breakthrough Curve of Experimental Vs Calculated Zinc Outside Peenya Industrial Area (PIA)

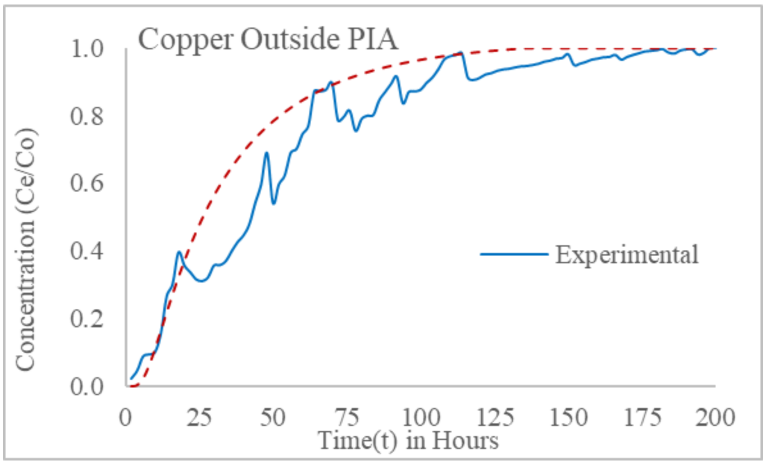

Figure 9d: Breakthrough Curve of Experimental Vs Calculated Copper Outside Peenya Industrial Area (PIA)

Conclusions

1. The soil column experiment apparatus are used to study the migration and attenuation of heavy metals (HMs) through an undisturbed soil column closer to field conditions. Soil column studies are pivotal in understanding heavy metals' behaviour and movement in soils. According to the soil column experiment, the lowest mobility is observed in clay soil (inside the PIA) rather than in sandy loam soil (outside the PIA). The overall study found that the mobility of Cr heavy metal in the soil column was higher than that of other metals in the soil column in both soils (inside and outside the PIA).

2. The current investigation found the dispersion coefficient in four undistributed soils outside the PIA and four undistributed soils inside the PIA. The hydrodynamic dispersion co-efficient 'D' when Cr, Ni, Zn and Cu solution was passed through 20cm soil column outside industrial area was 3.57 m^2/year, 1.99 m^2/year, 10.84 m^2/year, and 3.49 m^2/year and the solution was passed through 20cm soil column inside industrial area 5.22 m^2/year, 2.2 m^2/year, 8.08 m^2/year, and 6.57 m^2/year.

3. The present investigation describes the experimental Vs Calculated Values considerations and presents the Mathematica software tool for analysing solute conditions during infiltration from a source. The curves plotted by Mathematica and BTC are close to each other. Hence, it is possible to use the models based on the observed physical conditions to predict a dimensional flow pattern when experimentations can be avoided altogether. The mathematical models used in the present research help to predict the future effects of heavy metal pollution in the study region.

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Studie o disperzivitě těžkých kovů v nenarušených půdních sloupcích v průmyslové oblasti Peenya a kolem ní, Bengaluru, Indie

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Abstrakt

Tento článek analyzuje vliv indikátorů těžkých kovů na jednorozměrný transport polutantů přes nedistribuované sloupce půdy prováděný v laboratoři a experimentální data jsou porovnána s analytickými daty. V této studii se pomocí „Mathematica“ analyticky používá rovnice advekce-disperze k vyhodnocení transportu znečišťujících látek. Hodnotí kontaminaci těžkými kovy tím, že bere v úvahu vstupní koncentrace znečišťujících látek, a to, jak se mění s časem a hloubkou. Byly analyzovány výsledky experimentálního testu týkající se průlomových křivek, které odhalily základní vzorce migrace těžkých kovů.

Současný výzkum má najít rozptylový koeficient v průmyslové oblasti a kolem ní pro čtyři těžké kovy, tj. čtyři nenarušené sloupce půdy na stanici 1 (uvnitř) a čtyři nenarušené sloupce půdy na stanici 2 (venku). Koeficient hydrodynamické disperze „D“, když roztok chrómu (Cr), niklu (Ni), zinku (Zn) a mědi (Cu) prošel 20cm půdním sloupcem (každý kov na sloupec), byl mimo průmyslovou oblast 3,57 m^2/rok, 1,99 m^2/rok, 10,84 m^2/rok a 3,49 m^2/rok a 5,22 m^2/rok, 2,2 m^2/rok, 8,08 m^2/rok a 6,57 m^2/rok v průmyslové oblasti. Podle experimentu s půdním sloupcem je nejnižší mobilita pozorována v jílovité půdě (uvnitř průmyslové oblasti Peenya), spíše než v písčitohlinité půdě (mimo průmyslovou oblast Peenya). Tato zjištění zlepšují naše chápání znečištění těžkými kovy a poskytují základ pro předpovídání a řízení takového znečištění v průmyslových oblastech. „Mathematica“ použitá v tomto výzkumu pomáhá předpovídat budoucí účinky znečištění těžkými kovy ve studovaném regionu, a tím nás vybavuje znalostmi, abychom mohli přijímat proaktivní opatření.

Klíčová slova: *těžké kovy, mobilita, křivky průlomu (BTC), půdní sloupce, průmyslová oblast Peenya (PIA), kontaminace podzemních vod, hydrodynamická disperze.*

Přehledová studie využití odpadních minerálních vláken ve stavebnictví

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Souhrn

Odpady z minerální vlny (skleněné a čedičové) představují významný problém v oblasti recyklace stavebních materiálů. Tyto odpady vznikají nejen při výrobním procesu jako odřezky a odprašky (této problematice jsme se v našem výzkumu již věnovali[1]). Velké objemy tohoto odpadu vznikají i při demolici a rekonstrukci zateplovacích systémů budov, optimální využití tohoto odpadu v současnosti intenzivně zkoumáme. Překážkou při recyklaci je znečištění minerální vlny ostatním stavebním materiálem. Minerální vlna je v současnosti jako odpad skládkována.

Evropská legislativa zavádí poplatky za skládkování stavebních odpadů, a tím motivuje k vývoji recyklačních technologií. Vzhledem k rostoucímu objemu odpadu z minerální vlny, který se odhaduje na 2,82 milionu tun do roku 2030, je nezbytné hledat udržitelné řešení pro její opětovné využívání. Klíčovými faktory pro efektivní recyklaci jsou správné třídění a separace jednotlivých složek materiálů, což zatím v ČR a na Slovensku není dostatečně vyvinuto.

Recyklace odpadu z minerální vlny může přispět k ochraně životního prostředí a snížení nákladů na skládkování, pokud budou zajištěny vhodné technologie pro jeho zpracování. Studiem literatury byly zjištěny jako nejčastější směry použití odpadní minerální vlny – alternativní složka stavebních pojiv a náhrada jemných a velmi jemných podílů kameniva (přísada pro vznik nových izolačních hmot). Zaměření naší další týmové práce je v oblastech vývoje betonových prvků, omítek a alkalicky aktivovaných hmot.

Klíčová slova: *tepelná izolace budov, odpadní minerální vlna, čedičová a skelná vlákna, recyklace vláken, využití odpadního izolačního materiálu.*

Shrnutí současného stavu v oblasti minerální izolace

Odpady z minerální vlny (skleněné nebo čedičové) mohou vznikat již při její výrobě jako odřezky při jejím formátování nebo jako odprašky při jejím zpracování. Tyto odpady většinou nejsou znečištěné a jsou znovu využívány ve výrobě, nebo jsou kompaktovány na brikety, takže nezůstává žádný nevyužitý odpad. Jemné odprašky z filtrů mohou být podle různých studií použity například při výpalu slínku nebo při vytváření žáruvzdorných materiálů[2].

Odpadní minerální vlna přímo z výrobního procesu je lépe zpracovatelná díky své vysoké čistotě, než vlna, která se stala stavebním odpadem. Důležitou roli u této odpadní minerální vlny hraje metoda předběžné úpravy, tj. rozmělňování vláken a dosažení homogenity[3]. Množství minerální vlny, která se používá v zateplovacích systémech staveb, tvoří asi 60 % z celkového trhu izolačních materiálů. Při renovaci nebo demolici staveb vzniká velké množství odpadních izolačních materiálů[4].

Zateplování minerální vlnou se začalo intenzivně využívat od 70. a 80. let 20. století a odhaduje se, že doba životnosti zateplovacích systémů je minimálně 30 let. To znamená, že v blízké budoucnosti lze očekávat rozsáhlé rekonstrukce staveb, které byly zatepleny minerální vlnou. I když odpady z minerální vlny tvoří v České republice pouze malý podíl na celkovém objemu stavebních a demoličních odpadů, je nezbytné hledat efektivní způsoby jejich recyklace. S rostoucím počtem budov zateplených systémy, jejichž životnost se blíží ke konci, bude stále více potřeba řešit, jak s těmito odpady nakládat. Recyklace minerální vlny je důležitá nejen z hlediska ochrany životního prostředí, ale i vzhledem k rostoucí poptávce po technologiích pro opětovné využívání těchto materiálů.

Problémem recyklace odpadu z minerální vlny je složitost oddělení jednotlivých komponent kompozitního systému, který se běžně používá pro zateplení obvodových plášťů budov. Tento systém zahrnuje různé materiály, jako jsou stavební lepidla, mechanické spojovací prostředky, armovací sítě, základní nátěry, vrchní omítky a další, což činí recyklaci náročnou. V důsledku této složitosti je častější volba skládkování než recyklace, což není optimální z hlediska ekologického, ani ekonomického.

Dalším problémem je, že minerální vlna vznikající jako odpad při demolici nebo rekonstrukci staveb může být v některých zemích klasifikována jako nebezpečný odpad, zejména pokud byla vyrobena před rokem 1997. V té době byly při výrobě minerální vlny používány starší technologie, které mohly zahrnovat i azbest, což představuje vážné zdravotní riziko.

Klíčovým aspektem správného nakládání s odpady je třídění materiálů. Po vytřídění, zpracování, separaci a případně pulverizaci se může jednat o cennou surovinu do řady stavebních materiálů. Čím lépe jsou stavební a demoliční odpady tříděny, tím je recyklace efektivnější a kvalita recyklovaného materiálů vyšší. Tento systém třídění, sběru a zpracování odpadu z minerální vlny dosud nebyl nastaven v ČR ani na Slovensku. Minerální vlna je většinou skládkována současně s jiným stavebním odpadem. Vzhledem k tomu, že Evropská unie klade důraz na recyklaci stavebního a demoličního odpadu a zavádí poplatky za skládkování, se stále více zvyšuje motivace pro hledání a implementaci efektivních metod recyklace těchto materiálů. Také v České republice je skládkování minerální vlny zpoplatněno, což činí skládkování tohoto odpadu nákladnějším a podporuje rozvoj recyklačních technologií[5].

Objem celosvětové produkce odpadu z minerální vlny je 2,54 milionů tun. Odhaduje se, že objem odpadní minerální vlny roste lineárně z 2,25 milionu tun v roce 2010 na 2,54 milionu tun v roce 2020. Očekává se, že v roce 2030 vzroste na 2,82 milionu tun[3]. Je třeba poznamenat, že přesný odhad objemu odpadu z minerální vlny je problematický kvůli roztříštěnosti dostupných údajů[4].

Minerální vlna, její výroba a vlastnosti

Termín „vlna" je obecný název pro vláknité materiály, které vznikají zvlákňováním nebo tažením roztavených minerálů. Hlavními složkami jsou SiO_2, Al_2O_3, CaO a MgO, zatímco ostatní oxidy jsou považovány za nečistoty[6]. Chemické složení vlny závisí na použitých surovinách a u minerální vlny a skleněné vlny se obvykle mírně liší. Minerální vlna je uměle vyráběné anorganické vlákno nejčastěji z čedičové horniny. Skleněná vlna se vyrábí z křemene, sody a vápence, ale výhodně lze použít i recyklované sklo.

Odpady z výrobního procesu minerální vlny (ořezy z formátování atd.) lze znovu použít do procesu výroby. Vyrobená vlna má vlákna do desek pojená nejčastěji fenolformaldehydovou pryskyřicí, která může tvořit až 10 % hmot. konečného výrobku. Jako maziva se obvykle používají minerální nebo silikonové oleje v množství do 1 % hmot. konečného produktu. Vrstva minerální vlny může být také laminována například hliníkovou fólií, netkanými rohožemi ze skleněných vláken nebo kraftovým papírem.

Nejdůležitější vlastností minerální vlny je její tepelná vodivost (0,035 – 0,045 W/(m·K)). Pokud v konstrukci nedošlo k jejímu vystavení povětrnosti, i po cca 40 – 50 letech zůstává tepelná vodivost cca 0,04 W/(m·K). Jak minerální vlna i skelná vlna jsou klasifikovány jako nehořlavé (minerální vlna třída A1 nebo A2; skelná vlna třída A2). Recyklovaná minerální vlna může obsahovat různé nečistoty (součásti minerální vlny z výroby: pojiva, maziva, kraftový papír nebo hliníkové vrstvy; ze stavebního užití: armovací tkaniny, fólie, těsnicí pásky, spojovací prvky, případně biologická kontaminace – plísně a bakterie).

K zajištění vhodnosti odpadu z minerální vlny pro různá řešení opětovného použití je však zapotřebí více výzkumu. Některé systémy kategorizace nebezpečných látek klasifikují odpad z minerální vlny jako potenciálně karcinogenní látku, pokud je index rozpustné složky vyšší než 18 % a průměr vláken je < 6 μm. Nebezpečí zdravotních rizik způsobených vlákny minerální vlny je velmi nízké nebo žádné, a proto by měly být klasifikační systémy vyhodnoceny tak, aby zbytečně nebrzdily recyklační potenciál odpadu z minerální vlny. Skutečná rizika pro zdraví by však neměla být opomíjena[4].

Využitelnost odpadní minerální vlny

S ohledem na vysoký obsah chemicky inertních sloučenin, jako je oxid křemičitý (SiO_2), oxid vápenatý (CaO) a oxid hlinitý (Al_2O_3), které zlepšují vlastnosti požární odolnosti, se odpadní minerální vlna používá hlavně jako plnivo v kompozitních materiálech[1, 3].

V další nalezené studii se autoři Yliniemi a kolektiv[7] věnují zkoumání, jak různé mechanismy drcení ovlivňují fyzikální vlastnosti minerální vlny, včetně vzhledu, objemové hmotnosti a délky a šířky vláken. Výsledky studie ukazují, že metody založené na kompresi (vibrační kotoučový mlýn a hydraulický lis) zcela narušují vláknitost minerální vlny, zatímco metody založené na vysokých řezných rychlostech ovlivňují objemovou hmotnost a délku vláken jen mírně. Kromě toho tato studie identifikuje rychlou metodu, kterou lze novým způsobem použít k analýze velkého počtu vláken minerální vlny.

Odpad z minerální vlny tvoří hmotnostně jen malý zlomek celkového stavebního a demoličního odpadu, přesto vyžaduje velké přepravní a skládkovací kapacity kvůli své nízké objemové hmotnosti. Pro zvýšení jeho využitelnosti je nezbytné porozumět fyzikálním a chemickým vlastnostem tohoto odpadu, abychom ho mohli využít, např. jako vláknovou výztuž v kompozitech nebo jako doplňkový cementový materiál. V další práci se Yliniemi s kolektivem[8] věnoval chemické a fyzikální charakterizaci 15 vzorků skleněné a 12 vzorků kamenné vlny různého stáří odebraných z různých míst po celé Evropě. Současně provedl i rozsáhlou rešerši odborné literatury a uvádí tak chemické složení dalších 61 vzorků skleněné a kamenné vlny.

Vzorky skelné vaty vykazují malé rozdíly ve svém chemickém složení a výsledky složení jsou podobné běžnému sodno-vápenato-křemičitému sklu (4 – 11 % hmot. B_2O_3). Kamenná vlna má složení podobné čedičovému sklu, ale s různým obsahem vápníku, hořčíku a železa (5 – 13 % hmot.). Potenciálně toxické prvky (Cr, Ba, Ni, Cu a Pb) jsou přítomny v minerální i skelné vlně v nízkých koncentracích (<0,2 %). Oba typy vlny obsahují organickou pryskyřici (skelná vlna 8 % hmot.; minerální vlna 3 % hmot.), která se může po zahřátí nebo kontaktu s alkalickým roztokem rozložit na menší molekulární částice a amoniak. Odpady z minerální vlny mají relativně podobné rozložení délky a šířky, navzdory stáří a typu minerální vlny. Celkově mají oba typy odpadů z minerální vlny homogenní chemické a fyzikální vlastnosti ve srovnání s mnoha jinými minerálními odpady, díky čemuž je jejich využití jako druhotné suroviny slibné. Přesto je třeba brát v potaz vysoké procento respirabilních vláken (kolem 50 %), zejména při zpracování starých odpadů z minerální vlny, které mohou mít nízkou biologickou rozpustnost, a proto mohou být karcinogenní. Rozlišení mezi nebezpečnými a zdravotně nezávadnými vlákny minerální vlny na základě jejich chemického složení je náročné a nebezpečné vlastnosti minerální vlny by měly být stanoveny testy biologické rozpustnosti in vivo.

Alternativní složka pojiv

Minerální vlna má, díky svému vysokému obsahu amorfního SiO_2 (až 70 %) a CaO (až 20 %), potenciál být aktivní pucolánovou složkou. Protože pucolánová reakce probíhá na povrchu částic oxidu křemičitého, je měrný povrch nejdůležitějším faktorem pro průběh pucolánové aktivity[2].

Během procesu výroby minerální vlny se tvoří odpadní materiály, jako je vláknitý odpad a prach. Na jedné straně lze odpad z vláken minerální vlny recyklovat a vrátit do výrobní linky, ale prach z filtrů se obvykle pouze skládkuje. Na druhé straně lze odpad z minerální vlny použít jako vhodnou náhradu hrubého a jemného kameniva, čímž se ušetří náklady na přírodní kamenivo a minimalizuje se dopad likvidace na životní prostředí. Někteří výzkumníci[5,11,12] také poznamenávají, že složení odpadu z vláken minerální vlny je podobné jako u jiných pucolánových materiálů, jako je popílek, mletá granulovaná vysokopecní struska a mikrosilika.

Tým autorů Kubiliute, Kaminskas a Kazlauskaite[5] se ve své studii zaměřil na možnost využití prachu ze vzduchových filtrů během výroby minerální vlny jako mikroplniva do portlandského cementu. Výsledky ukázaly, že přísada odpadního prachu zvyšuje počáteční hydrataci cementu. Při použití 5, 10 a 15 % hmot. prachového aditiva byla pevnost vzorků v tlaku po 28 a 90 dnech hydratace větší než u vzorku čistého portlandského cementu. Bylo zjištěno, že odpady z minerální vlny mohou v závislosti na velikosti částic působit buď jako cementový materiál, nebo jako inertní plnivo v kompozitech na bázi cementu. Kromě toho bylo zjištěno, že 10 – 40 % hmot. odpadní přísady z minerálních vláken snižuje pórovitost a mění mikrostrukturu kompozitů na bázi cementu, což snižuje migraci chloridových a jiných iontů.

Studie autorů Cheng, Ling a Chuang[9] zkoumala vlastnosti kompozitů na bázi cementu s přídavkem různých odpadů z minerální vlny (distribuce částic v rozmezí 17 – 250 µm, z nichž 30 % je menší než 150 µm). Přídavek 10 % odpadu z minerální vlny do kompozitů na bázi cementu (w/c 0,55 a 0,65) způsobil v porovnání s kontrolními vzorky:

- zvýšení pevnosti v tlaku o 19 % a 18 %,
- zvýšení pevnosti v tahu při štípání o 33 % a 26 %,
- snížení odolnosti proti oděru o 4 % a 5 %,
- snížení absorpce o 33 % a 28 %,
- zvýšení odporu o 251 % a 253 %,
- snížení celkového průchodu náboje o 73 % a 70 %.

Odpad z minerální vlny lze použít jako částečnou náhradu jemného kameniva a doplňkový pojivový materiál v závislosti na velikosti jeho částic (u částic menších než 75 µm pucolánová reakce). Hrubší částice minerální vlny mají potenciál zachytit/minimalizovat vznik smršťovacích trhlin a inhibují vnitřní šíření trhlin.

Cílem výzkumu týmu M. G. Mediros[10] bylo zjistit pucolánový potenciál odpadní minerální vlny Rockwool, která je převážně vyráběná z čediče. Největší inovací této práce byla analýza možnosti a efektu nahrazení portlandského cementu odpadem minerálních vláken Rockwool. Výsledky provedených testů ukazují, že odpad Rockwool je klasifikován jako třída II A, tj. neinertní (ne nebezpečný), lze ho charakterizovat jako amorfní pevnou látku. Pozorování pasty hydroxidu vápenatého s mletými minerálními vlákny v SEM (28 dnů stáří) a výsledky Chapelleova testu neumožnily prokázat pucolánovou reakci mezi odpadem Rockwool a hydroxidem vápenatým. Zdá se však, že pucolánová reakce začíná později, což ukazují další pozorování v SEM a provedená termogravimetrická analýza ve vzorcích po 90 dnech.

Další studie[11] byla zaměřena na hodnocení vlastností kompozitů na bázi cementu s použitím různých obsahů odpadní minerální vlny (10 %, 20 %, 30 % a 40 % hmot. cementu) jako částečné náhrady portlandského cementu v maltách. Výsledky testů ukazují, že kompozity obsahující odpady z minerální vlny mohou zlepšit mechanické vlastnosti a snížit propustnost.

Studie provedená týmem Wei-Ting Lin[12] se zaměřuje na zkoumání vlastností kompozitních materiálů na bázi cementu, do kterých byl přidán různý podíl recyklované minerální vlny, a porovnává je s kompozity obsahujícími popílek a mletou granulovanou vysokopecní strusku (GGBS). Recyklovaná minerální vlna byla rozdrcena na částice menší než 75 µm a na základě chemického složení a distribuce velikosti částic vykazuje podobné vlastnosti jako jiné pucolánové materiály, jako jsou popílek a GGBS. To znamená, že recyklovanou minerální vlnu lze využít jako doplňkový cementový materiál, který má podobný účinek na zpevnění směsi. Experimentální výsledky ukázaly, že částečné nahrazení cementu recyklovanou minerální vlnou přináší zlepšení v několika klíčových aspektech, jednak významně zvyšuje pevnost v tlaku a současně pozitivně ovlivňuje strukturu pórů v cementové matrici. Tento efekt se projevuje zejména při použití náhradní dávky mezi 10 % až 30 % cementu. Studie naznačuje, že recyklovaná minerální vlna je účinnou příměsí, která může zlepšit mechanické vlastnosti betonových kompozitů. V tomto kontextu by mohla být recyklovaná minerální vlna zajímavou alternativou k tradičním příměsím, jako je popílek nebo GGBS.

Alternativní surovina – malta

Kolektiv Jana Trejbala[4] pracoval na vývoji omítkové malty s využitím odpadních minerálních vláken. Odpad v podobě prachových částic zachycených na dvojitém filtru recyklační linky byl v omítkové směsi použit jako mikroplnivo. Cílem bylo použít co nejvíce recyklovaného materiálu při zachování mechanických vlastností referenční malty (standardní směs bez přísad). Bylo navrženo šest směsí lišících se od sebe množstvím použitého recyklovaného odpadu od 0 do 1,0 % hmot. z celé směsi. Použití mikrovláken potvrdilo očekávané funkce v maltové směsi:

- náhrada jemné frakce přírodního kameniva (prachové částice),
- náhodně rozptýlená a orientovaná mikrovýztuž (krátká vlákna),
- shluky vláken jako izolační kamenivo.

K. Kalinowska-Wichrowska s kolektivem[13] prezentuje výsledky výzkumu, který potvrzuje možnost opětovného využití odpadních stavebních materiálů jako náhrady přírodního kameniva. Pro výzkum byly použity jemné frakce recyklovaného betonu, odpadních izolačních materiálů (kamenná vlna a sklolaminát) a recyklovaný písek. Vlastnosti zkoumaných receptur byly porovnávány na základě výsledků pevnosti v tlaku, pevnosti v ohybu, nasákavosti, povrchové tvrdosti (Shore D) a studia mikrostruktury (SEM). Výsledky ukazují, že všechny popisované materiály by mohly být přijatelným řešením pro redukci používání přírodních zdrojů.

Diplomová práce Bc. Čermáka[14] se věnuje možnosti využít minerální vlákna v cementových maltách a stěrkových a lepicích hmotách. Minerální vlákna v cementové maltě mohou snižovat objemovou hmotnost a součinitel tepelné vodivosti, vliv mají i na pevnostní charakteristiky. Minerální vlákna v cementové maltě výrazně snižují součinitel tepelné vodivosti λ a zlepšují její izolační schopnost. Přídavek minerálních vláken do průmyslově vyráběné lepicí a stěrkové hmoty působil při nanášení vady povrchu stěrky. Využití vláken je možné, ale není zcela bez problémů.

C. P. Ramírez s kolektivem[15] se věnovala výzkumu trvanlivosti cementových malt s přídavkem odpadní izolační vlny. Příspěvek o výsledcích experimentů podrobně popisuje výrobu vzorků cementové malty obsahující různé typy vláken z izolačního odpadu (různé druhy: odpad ze skelných vláken, odpad z minerální vlny a směsný odpad). Na vzorcích malt byla testována mrazuvzdornost, krystalizace solí, propustnost vodní páry, obsah uzavřeného vzduchu a doba zpracovatelnosti. Studované malty vykazují dobré vlastnosti při zmrazování, což zaručuje jejich použití ve venkovním prostředí. Malty prokázaly nižší odolnost vůči krystalizaci solí v důsledku zvýšení jejich porézních struktur. V důsledku kapilárního působení jsou tyto malty náchylnější k transportu kapalin ve svém pórovém prostředí (roztok vody, solí).

Cílem práce týmu P. O. Awoyera[16] bylo zhodnotit použití minerální vlny a rýžové slámy ke zlepšení tepelně izolačních vlastností malt z portlandského cementu. Vzorky cemento-pískové malty (40x40x160 mm) byly vyrobeny s přídavky minerální vlny a rýžové slámy od 0 do 50 % hmot. Porovnávány byly referenční směsi (bez přídavku) s modifikovanými recepturami. Sledované vlastnosti – nasákavost, pevnost v ohybu a tlaku, tepelná vodivost a mikrostruktura pomocí rastrovací elektronové mikroskopie (SEM). Výsledky pro malty s minerální vlnou a vlákny rýžové slámy vykazovaly významný pokles tepelné vodivosti malty, tj. zlepšení její izolační schopnosti. Pevnost v tlaku u většiny modifikovaných vzorků klesla, ale byl zaznamenán nárůst pevnosti v ohybu. Provedené zkoušky prokázaly možnost použití vybraných vláken pro izolační malty z portlandského cementu.

Alternativní surovina – malty s požární odolností

Cílem výzkumu provedeného týmem C. P. Ramírezové[17] bylo analyzovat požární odolnost cementových malt s minerální vlnou z recyklace stavebních a demoličních odpadů. Týmem byl navržen experimentální plán pro analýzu termomechanického chování před a po testování malt s různými typy recyklovaných vláken. Vzorky malt s recyklátem byly vystaveny přímému ohni dosahujícímu maximální teploty 700 °C. Hodnoty pevnosti v tlaku všech malt vystavených vysoké teplotě klesají, i když zůstávají na optimálních hodnotách pro použití podle normových požadavků. Výsledky ukazují, že povrchová tvrdost všech malt se po požáru prakticky nemění, zatímco malty s přídavky vláken dosáhly výrazně lepších pevností v ohybu po požární zkoušce ve srovnání s referenční maltou. Cementové malty se zbytky minerální vlny jsou nehořlavé a neuvolňují dusivé plyny a výpary v případě požáru. Při teplotách do 700 °C si zachovávají pevnosti a mají velmi nízkou tepelnou vodivost, takže by dokázaly ochránit další prvky hořlavých materiálů a zabránit tak šíření požáru. Přidání odpadních vláken může být, z hlediska mechanicko-tepelného chování po požáru, udržitelnou alternativou k běžně používaným komerčně používaným vláknům.

Kolektiv A. Bala[18] se věnoval posouzení vlivu vyztužení skelnou vatou a žáruvzdorného povlaku na chování samozhutnitelné malty (SCM) při běžných a zvýšených teplotách (200, 400, 600, a 800 °C).

16 receptur SCM malty bylo navrženo s 25 % popílku a s použitím přídavku (0; 0,5; 1 a 1,5 %) a měnícím se efektivním poměrem vody k cementu (w/c: 0,43; 0,49; 0,55 a 0,70). Na čerstvých maltách byla měřena reologie pomocí rozlití kužele, „V – nálevky“ a reometru BT2. Dále byla vyrobena zkušební tělesa (krychle 100x100x100 mm a trámce 75x75x300 mm) a jejich další vlastnosti byly zjišťovány po 28 dnech zrání. Část zkušebních těles byla povrchově ošetřena tepelně odolným nátěrem. Jde o nátěr dodávaný v práškové podobě (fa UGAM Technology, Vadodara, Gujrat, Indie) a podle EDX analýzy obsahuje tyto hlavní složky: oxidy prvků Al, Si a Ti. Aplikace tepelně odolného povlaku byla významnou ochranou vzorků SCM až do maximální teploty ohřevu 800 °C, kdy došlo k nepatrnému poklesu mechanických vlastností, zejména pevnosti. Vzorky malt bez povrchového ošetření nátěrem měly naopak, vlivem působení vysokých teplot, velké ztráty mechanických vlastností (asi 45 až 65 % pevnosti). Termogravimetrická (TG) analýza prášku SCM odhalila tepelnou stabilitu směsi SCM až do 1000 °C, kdy k významné ztrátě hmotnosti došlo zahřátím na teplotu 400 °C (ztráta 0,3 %) a 800 °C (7,5 %).

Alternativní surovina – lehký beton

Perspektivním směrem rozvoje efektivních recyklačních technologií může být opětovné použití odpadů z minerální vlny v kompozitech na bázi cementu. Řada výzkumů prokazuje postupné nahrazování přírodního kameniva v betonech různými druhy odpadu. Mletý odpad z minerální vlny s distribucí velikosti částic v rozmezí od 17 do 250 μm lze použít jako náhradu jemného a ultra jemného kameniva se zlepšením hlavních vlastností výrobku[2].

Výzkum použití vláken minerální vlny v oblasti vývoje lehkého betonu (LWC) je vzácný. Cílem studie provedené týmem Y. Z Shyong[19] bylo zkoumat fyzikální a mechanické vlastnosti LWC s použitím vláken minerální vlny (0 – 15 %) a s různým poměrem záměsové vody (w/c: 0,4; 0,5 a 0,6). Navrženo bylo 21 směsí a sledovány byly tyto vlastnosti: hustota, pórovitost, nasákavost, pevnost v tlaku, pevnost ve smyku a v ohybu. Výsledky ukázaly, že při dávce 15 % minerální vlny došlo ke značnému snížení objemové hmotnosti LWC (až 73% snížení). Objemové hmotnosti vzorků pro obsah vláken od 2,5 do 10 % jsou 800 až 2000 kg/m³, což lze klasifikovat jako LWC. Pouze určitá receptura splnila požadavky použití LWC jako nosné vnitřní stěny. Klíčovou roli v přidávání minerální vlny do LWC hraje velikost a distribuce vláken v objemu hmoty a je takto následně ovlivněna morfologie, velikost pórů, a tedy schopnost zvukové a tepelné izolace.

Alternativní surovina – keramika

Experimentální studie provedená Korpajevem s kolektivem[20] zkoumala použití mletého odpadu z kamenné vlny (SWW) na vlastnosti pálených hliněných cihel. Pro stanovení maximálních směšovacích poměrů byly vzorky cihel připraveny ze směsí jíl/SWW v poměrech 95/5, 90/10, 87,5/12,5 a 82,5/17,5 hmot. Po výpalu (850, 950 a 1050 °C) byly stanoveny fyzikální, tepelné a mechanické vlastnosti cihel. Výsledky prokázaly, dle procentuálního podílu SWW vneseného do výrobní suroviny, že může dojít ke snížení objemové hmotnosti pálených cihel až o 13 %. Vypálené cihly (výpal 1050 °C) s přídavkem 10 % SWW dosáhly zvýšení tepelné izolace až o 20,75 %, pozitivní vliv měl přídavek i na trvanlivost (zejména mrazuvzdornost). Podle zjištění lze použít při výrobě cihel jako maximální míru náhrady jílu 17,5 % SWW. Jde tak recyklovat velké množství odpadu a zároveň vyrobit cihly s požadovanými vlastnostmi.

Chen s kolegy[21] provedl studii, která zkoumala opětovné použití minerální vlny a recyklovaného skla při výrobě keramických pěn. Při spékání minerální vlny a odpadního skla bylo jako pěnidla použito SiC. Cílem výzkumu bylo porozumět vlivu složení a podmínek slinování na vlastnosti a mikrostrukturu keramické pěny. Optimální skladba keramické pěny byla tvořena 40 % hmot. odpadní minerální vlny, dále podíly odpadního skla a odpadního křemičitého písku a 2 % hmot. SiC, spékaných při 1170 °C (rychlost ohřevu 20 °C/min, 20 min výdrž při max. teplotě). Vyrobené keramické pěny měly objemovou hmotnost 0,71 g/cm^3 a rovnoměrné rozložení velikosti pórů. Výzkum ukazuje, že z odpadní minerální vlny lze vytvořit keramické pěny vhodné pro tepelnou izolaci. Ačkoliv autoři v textu mluví o vzniku keramické pěny, na základě chemického složení lze konstatovat, že se jedná o materiál v ČR označovaný jako pěnové sklo.

Recyklaci skelné vaty jako tavidla při výrobě keramiky na bázi jílu a odpadu se věnoval tým A. Adedirana[22]. Jako prekurzory byly vybrány komerční kaolinový jíl a dva průmyslové odpady, konkrétně křemičitý živcový písek a měděná struska. Bylo připraveno šest receptur (3 vzorky s/bez skelné vaty) a vzorky byly vypalovány při 750, 850 a 950 °C. Vzorky byly charakterizovány pomocí rentgenové difrakce (XRD), skenovací elektronové mikroskopie (SEM) se stanovením prvků (EDS), diferenční skenovací kalorimetrie (TG/DSC), absorpce vody, zdánlivé hustoty a zkoušek pevnosti v tlaku a ohybu. Výsledky ukázaly, že začleněním 10 % hmot. skelné vlny do směsí vznikla keramika s lepšími fyzikálními, mechanickými a mikrostrukturními vlastnostmi. Vzorky s křemenným pískem a skelnou vatou po výpalu (950 °C) dosáhly hodnot pevnosti v tlaku až 117 MPa a nasákavosti 2 %. U keramiky na bázi strusky a kaolinu byl však tavicí efekt skelné vlny méně významný, to pravděpodobně kvůli rozdílům v jejich chemickém složení, mineralogii a distribuci částic. Schopnost tavení skleněné vlny může snížit teplotu slinování a následně snížit náklady na výrobu keramiky.

Příspěvek R. Stonyse a kolektivu[2] se zabýval odpadem z výroby minerální vlny (kupolový prach CD, amorfní SiO_2, průměr částic prachu je podobný jako u mikrosiliky 30 až 150 nm) a jeho opětovným použitím při výrobě žárobetonů s hlinitanovým cementem. Filtrační sedimenty z výroby minerální vlny mají velmi malé rozměry, a proto nejsou snadno recyklovatelné. Ultra jemný odpadní prach nahradil v recepturách mikrosiliku, která je jedním z nejrozšířenějších ultrajemných aditiv do žáruvzdorných betonů. Mikrosilika zvyšuje hustotu a zlepšuje vlastnosti žárobetonu díky své pucolánové aktivitě a malé velikosti částic. Pro návrh žárobetonu bylo ve směsích použito 1, 2 a 3 % odpadního prachu. Na vzorcích žárobetonu byly stanoveny vlastnosti po vytvrzení, vysušení (105 °C) a výpalu (800 a 1000 °C). Sledovány byly vlastnosti: objemová hmotnost, rychlost průchodu ultrazvukové vlny, pevnost v tlaku bez tepelné zátěže a odolnost proti tepelnému šoku. Z výsledků fyzikálních a mechanických vlastností plyne, že jako optimální teplota výpalu je 800 °C s dávkováním CD do 2 %. Přínosem výzkumu je zjištění, že metoda zpracování CD navržená v této práci, je vhodná jak z ekologického, tak technologického i ekonomického hlediska.

Alternativní surovina – pěnové sklo

Možnosti využití odpadní minerální vlny pro výrobu pěnového skla za nízké teploty (800 °C) se věnovala studie R. Ji a kolektivu[23]. Nově vyvinutá metoda výroby pěnového skla používala jako hlavní suroviny odpady z minerální vlny a odpadního skla z procesu výstavby a demolice. V navržené receptuře byly použity přísady s funkcí pěnidla, tavidla a stabilizátoru pěny (uhličitan vápenatý $CaCO_3$, borax $Na_2B_4O_7 \cdot 10H_2O$, fosforečnan trisodný dodekahydrát $Na_3PO_4 \cdot 12H_2O$). Na vlastnostech pěnového skla (objemová hmotnost, mikrostruktura) byly zkoumány vlivy různého obsahu jednotlivých přísad a různé teploty slinování. Výsledky experimentu ukázaly, že optimální složení surovin se pohybovalo v rozmezí 40 % hmot. odpadní minerální vlny, 60 % hmot. odpadního skla, 20 % hmot. boraxu, 1 –2 % hmot. uhličitanu vápenatého a 2 % hmot. fosforečnanu. Vzorek slinutý při 800 °C měl nejrovnoměrnější rozložení pěnové struktury a nízkou objemovou hmotnost 0,7 g/cm^3.

Alternativní surovina – kompozit na bázi sádry

Ve výzkumu A. Zaragoza-Benzal s kolektivem[24] byl představen nový sádrový kompozitní materiál, ve kterém byly tradiční suroviny částečně nahrazeny tepelně izolačním odpadem (polystyren EPS a minerální vlna) z renovace fasád. Výsledným návrhem je nový lehký sádrový kompozit s náhradou až 14,7 % hmot. původního materiálu s odpadem EPS a s přidáním minerální vlny jako výztuže (0,375 % hmot.). Podle výsledků má nový materiál o 20,3 % nižší objemovou hustotu než tradiční sádrový kompozit, tedy má i o 30,4 % nižší tepelnou vodivost. Tyto nové odlehčené sádrové kompozity lze použít v kombinaci s lehkými ocelovými rámy jako dokončovací desky ve stěnových systémech, a to při snížení celkového tepelného odporu stěny až o 10,6 % (tloušťka 25 mm). Mechanická odolnost nového materiálu překračuje referenční hodnoty stanovené současnými normami, snížení celkové i kapilární absorpce vody ve srovnání s tradiční sádrou, což zvyšuje odolnost materiálu a jeho vynikající tepelné vlastnosti po celou dobu životnosti.

Alternativní surovina – alkalicky aktivované hmoty

Pokusy vytvořit ekologičtější alternativu k portlandskému cementu nejsou nové. Odpadní kamenná vlna obsahuje vysoké množství oxidů (SiO_2, Al_2O_3, CaO), které jsou vhodné jako prekurzory pro výrobu alkalicky aktivovaných materiálů[2].

Článek týmu Łaźniewska-Piekarczyk a Dominik Smyczek[25] pojednává o vlivu aditiv odpadních vláken minerální vlny na geopolymerní pojivo. Článek popisuje účinnou metodu rozmělňování vlny na prášek a metodiku tvorby vzorků geopolymerů, označených G1 pro geopolymer na bázi skelné vaty a G2 pro geopolymer na bázi kamenné vlny. Sledovanými vlastnostmi byla pevnost v tlaku a ohybu a součinitel tepelné vodivosti geopolymeru s přídavkem minerálních vláken. Klíčovým prvkem článku je ověření, zda přídavek vláken minerální vlny pozitivně ovlivňuje vlastnosti geopolymeru. Získané výsledky dokazují, že přidání vláken výrazně zlepšuje pevnost v tahu za ohybu. Pro recepturu G1 je poměr pevnosti v tlaku k pevnosti v tahu za ohybu 18,7 %. U vzorků G2 však bylo dosaženo ještě lepšího poměru pevnosti v tlaku k hodnotám pevnosti v tahu za ohybu 26,3 %. Získaný průměrný koeficient tepelné vodivosti byl 1,053 W/(m·K) pro vzorky řady G1 a 0,953 W/(m·K) pro vzorky řady G2. Získané závěry ukazují korelaci mezi pórovitostí a pevností v tlaku a koeficientem tepelné vodivosti. Čím vyšší pórovitost, tím lepší tepelná izolace materiálu a horší pevnost v tlaku.

Článek H. Dai s kolektivem[26] představuje vývoj tepelně izolačního geopolymerního materiálu. Jde o porézní kompozit na bázi kaolinitu s alkalickou aktivací při pokojové teplotě a vyztužení vlákny z minerální vlny. Zkoumán byl účinek obsahu vláken minerální vlny a vlivu tepelného zpracování na komplexní vlastnosti porézního geopolymeru. Od přídavku vláken z minerální vlny se očekávalo zlepšení mechanických vlastnosti porézního geopolymeru, od tepelného zpracování pak vznik porézní struktury, tj. zlepšení tepelné izolace geopolymeru na bázi kaolinitu. Vzorek s obsahem 15 % hmot. minerální vlny vykazoval poréznost ~90 %, hustotu 0,118 g/cm^3, tepelnou vodivost 0,057 W/(m.K) a maximální pevnost v tlaku 0,66 MPa. Tento nový tepelně izolační materiál má obrovský potenciál v oblasti úspory energie budov.

V příspěvku Luo a Yu[27] je zkoumán potenciál využití odpadu z minerální vlny jako prekurzoru a vláknové výztuže v geopolymeru s popílkem třídy F. Použití těchto odpadů, zejména ve formě jemných částic (dvě různé předúpravy vláken), urychluje proces geopolymerizace, což vede ke zvýšené tvorbě gelu a zvýšené absorpci Al v gelu N-A-S-H. Vliv reaktivity a rozměrů odpadní vlny na hybridních geopolymerech byly systematicky studovány na základě reakční kinetiky a produktů, mikrostruktury, smrštění při sušení, mechanické pevnosti a studia tepelného chování (výpal při 800 °C).

Výzkum týmu Pavlín[28] nabídl nový pohled na využití odpadní minerální vlny (kamenná vlna, skelná vlna) a pomocných pojiv při vývoji alkalicky aktivovaných směsí pro 3D tisk. Zjištění podtrhují robustní mechanický výkon a tepelnou stabilitu těchto materiálů a staví je jako slibné kandidáty pro aplikace vyžadující odolnost při zvýšených teplotách. Díky přidání minerální vlny a pomocných pojiv vykazovaly alkalicky aktivované 3D tištěné produkty pevnost v tlaku přesahující 50 MPa po 28 dnech vytvrzování (při T0). 3D tištěné vzorky byly při rostoucí teplotě chemicky i mineralogicky stabilní do 700 °C. S rostoucí teplotou (nad 800 °C) se objevily nové mineralogické fáze a došlo ke snížení obsahu amorfních složek (z cca 86 % hmot. na 46 % hmot.).

V další studii provedené kolektivem K. M. Klima[29] byly zkoumány účinky odpadu z minerální vlny v alkalicky aktivovaném umělém kamenivu vyvíjeném pro vysokoteplotní aplikace. Byly zkoumány parametry aktivačního a vytvrzovacího procesu. Stanovení vlastností proběhlo při pokojové teplotě a při vysoké teplotě (1000 °C) na prostém kamenivu a po začlenění do geopolymerního kompozitu. Při optimálním režimu vytvrzování (za pokojové teploty) po dobu 3 dnů vzniklo umělé kamenivo s objemovou hmotností v rozmezí od 1960 do 2090 kg/m^3 a pevností v tlaku 7,0 až 7,9 MPa. Sodný aktivátor s vysokou viskozitou způsobil nepravidelnější tvar zrna s nižší hustotou částic a pevností v tlaku, oproti kamenivu aktivovanému draselným aktivátorem. Vysoká krystalinita byla pozorována v K-aktivovaných agregátech, což způsobilo lepší tepelnou stabilitu.

Studie C. H. Koh s kolektivem[30] zkoumala recyklaci kamenné vlny ze stavebního a demoličního odpadu pro výrobu lehkého alkalicky aktivovaného kameniva určeného pro izolaci podlahy. Kamenivo bylo vyrobeno alkalickou aktivací z různých podílů mleté a původní kamenné vlny. Výsledkem byla objemová hmotnost v rozmezí 720 až 850 kg/m^3 a tepelná vodivost od 0,075 do 0,094 W/(m·K). Morfologie vlákna kamenné vlny v původním stavu ovlivnila reologii, dala vzniknout většímu počtu pórů i defektů, což vedlo ke snížení mechanické pevnosti. Hydrotermální simulace ukázaly, že sestava podlahy částečně vyplněná vyrobeným kamenivem vykazovala snížení obsahu vody a zvýšení povrchové teploty podlahy.

Alternativní surovina – lehké kamenivo

A. B. López-García s kolektivem[31] zkoumali použití skleněné vlny (GW) a minerální vlny (SW) jako složky při výrobě lehkého kameniva (LWA). Oba odpady dle studie mohou být vhodnou surovinou (hustota 1,3 – 1,5 g/cm^3 a mechanická pevnost 2 – 6 MPa). Při použití GW se předpokládá výrazné snížení vypalovací teploty (700 °C) oproti běžně používaným teplotám (kolem 1200 °C) při výrobě těchto materiálů, což by znamenalo značné úspory energie. Technologické vlastnosti LWA získané ze skleněné vlny a minerální vlny vykazovaly vlastnosti analogické vlastnostem komerčního lehkého kameniva (hustota, pórovitost, nasákavost a mechanická pevnost). Tepelně izolační materiály a lehké kamenivo dlouhodobě patří mezi nejpoužívanější materiály ve stavebnictví, proto byl hodnocen metodou LCA i dopad na životní prostředí spojený s výrobou lehkého kameniva s SW a GW ve srovnání s tradičním procesem. Téměř u všech analyzovaných kategorií vlivu umělého kameniva vyrobeného z minerální vlny bylo pozorováno významné zlepšení parametrů životního prostředí.

Alternativní surovina – kompozitní zvuková izolace

Hemmati s kolektivem[32] se zabýval složitou rovnováhou mezi pohlcováním zvuku, tepelnou izolací a nákladovou efektivitou dřevovláknité desky – minerální vlna – cementové desky (WRCB). Desky WRCB s obsahem dřevěných vláken, portlandského cementu, minerální vlny a chloridu vápenatého byly vyrobeny v různých tloušťkách (20 – 60 mm) a hustotách (400, 500 a 600 kg/m^3). WRCB vykazovala průměrnou zvukovou absorpci (SAA) a efektivní tepelnou vodivost (K_{eff}). Desky WRCB s tloušťkami od 30 do 50 mm a hustotami 400 – 500 kg/m^3 vykazovaly téměř ideální úrovně absorpce mezi 1000 a 2000 Hz, což vyhovuje současným architektonickým požadavkům. Využití metody „Response Surface Methodology“ umožnilo optimalizovat vlastnosti desky (tj. hustota 452,8 kg/m^3 a tloušťka 37,8 mm) s maximální SAA, při současné minimalizaci K_{eff} a nákladů. Výsledky ukázaly významný vliv tloušťky a hustoty na akustické a tepelné vlastnosti WRCB desky.

Alternativní surovina – tepelná izolace

Článek M. Domonkos[33] se věnoval studiu tepelných a strukturálních vlastnosti izolace z recyklované minerální vlny získané ze stavebního a demoličního odpadu. Měřením tepelného toku byl na vzorcích stanoven základní parametr charakterizující tepelně izolační materiály – tepelná vodivost. Zkušební vzorky byly vyrobeny z mikromletého a nasekaného odpadního materiálu (objemová hmotnost 50 – 120 kg/m^3). K testům byly připraveny 3 vzorky (nekontaminovaný referenční vzorek Supafil Loft 045; mikromletá a nasekaná odpadní minerální vlna). Vzorky vyrobené z recyklované izolace měly vyšší součinitel tepelné vodivosti než referenční vzorky, přesto vykazovaly přijatelné izolační vlastnosti, protože jejich součinitel tepelné vodivosti se pohyboval v rozmezí 0,040 – 0,055 W/(mK). Sekaná odpadní minerální vlna je vhodná jako výplňová izolace. Mikrofrézovaný materiál má širší využití, a to jako recyklovaná sypaná/foukaná i výplňová izolace.

Závěry

Recyklace odpadů z minerální vlny, jako je skleněná a čedičová minerální vlna, je klíčovým tématem v oblasti udržitelnosti a ochrany životního prostředí. Minerální vlna je běžně používána pro své izolační schopnosti, ale jako odpad představuje technologickou výzvu. Provedená rešerše článků o recyklaci odpadů z minerální vlny nám umožnila získat přehled o různých oblastech jejího využití. Aktuální stav poznání ukazuje, že po vhodném přečištění a úpravě mohou být minerální vlákna efektivně využívána jako náhrada drobného kameniva nebo jemnozrnných částic v betonech a maltách. Velmi jemně mletá minerální vlna může přispívat ke zlepšení vlastností těchto směsí díky své pucolánové aktivitě. Směr recyklace minerálních vláken v alkalicky aktivovaných materiálech může být efektivním krokem k ekologicky šetrným a vysoce výkonným stavebním materiálům. Další slibný směr využití minerální vlny je při výrobě pálených keramických cihel nebo jako součásti keramických pěn, resp. pěnového skla. Minerální vlna může nejen zlepšit mechanické a izolační vlastnosti produktů, ale také přispět k úsporám energie a snížení emisí CO_2 při výrobě stavebních materiálů.

Poděkování

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Review study on the use of waste mineral fibres in the construction industry

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Summary

Mineral wool waste (glass and basalt) constitutes significant problem in the field of recycling of construction materials. This waste is created not only within production process as cuttings and dust (we have already dealt with this issue in our research), but also within demolition and reconstruction of thermal insulation system of buildings, the optimal use of this waste is currently under intensive research. A barrier for its recycling is contamination of mineral wool with other construction material and sizeable volume for storing to subsequent recycling. Mineral wool is currently dumped as a waste. European legislation implements charges for construction waste disposal, and therefore motivates to development of recycling technologies. Regarding to increasing volume of mineral wool waste, which is estimated 2.82 million tons up to 2030, it is necessary to find sustainable solution for its reuse. Key factors for effective recycling are proper sorting and separation of individual components, which is not sufficiently established in the Czech Republic and Slovakia so far. Recycling of mineral wool waste can contribute to environment protection and decreasing of disposal costs, if suitable technologies for its treatment are implemented. By studying the literature, the most frequent directions of use of waste mineral wool were identified as an alternative component of construction binders (an additive increasing strength characteristics) and replacement of fine and very fine aggregate fractions (an additive for the creation of new insulation materials). The scope of our next work is in the field of development of concrete elements, plasters and alkali-activated materials.

Keywords: *Thermal insulation of buildings, waste mineral wool, basalt and glass fibres, fibre recycling, utilization of waste insulation material*

VÁŽENÍ PŘÍZNIVCI APLIKOVANÉHO VÝZKUMU A RIZIKOVÉHO MANAGEMENTU,

dovolujeme si vás pozvat na další ročník Týdne výzkumu a inovací pro praxi a životní prostředí (TVIP), který letos proběhne v termínu 14. – 16. října 2025 v Hustopečích u Brna. Nový ročník opět zastřešuje dvě tradiční specializovaná odborná setkání: konferenci APROCHEM a symposium ODPADOVÉ FÓRUM. Symposium se mimo aktuální projekty z oblasti odpadů, ochrany vod a ovzduší, blíže zaměří na odpady ze stavebnictví, textilního průmyslu a elektroodpad.

APROCHEM: Konference tematicky pokrývá oblast řízení rizik a bezpečnosti. Zaměřuje se zejména na **řízení průmyslových rizik a rovněž na rizika při správě regiónů, měst a obcí.** Konference odráží význam výzev vyplývajících ze změn ovlivňujících naši společnost v oblasti širokého spektra rizikového managementu (mezinárodní bezpečnostní situace, bezpečnost kritické infrastruktury v souvislosti s uplatňováním nových technologií, rozšiřováním energetického mixu o alternativní zdroje energie, změnami klimatu atd.).

RIZIKOVÝ MANAGEMENT A PREVENCE A ODSTRAŇOVÁNÍ HAVÁRIÍ

- Posuzování a řízení rizik
- Prevence závažných průmyslových havárií
- Zkušenosti z odstraňování následků havárií
- Rizika při nakládání s chemickými látkami a přípravky
- Rizika související s nanomateriály (např. ve vztahu k potravinám)
- Rizika vyplývající z nových výzev (změna klimatu, nástup chytrých technologií, využití alternativních zdrojů energie a dopady geopolitických změn)
- Bezpečnost a hygiena práce

ODPADOVÉ FÓRUM: 19. ročník symposia pokračuje v prezentaci výsledků výzkumných projektů z celé oblasti průmyslové a komunální ekologie z oblasti **odpadů**, **ochrany vod** a **ovzduší**. Navíc budeme věnovat zvýšenou pozornost výzkumu cílícímu na aplikaci principů cirkulární ekonomiky a udržitelnosti ve **stavebnictví**, **textilním průmyslu** a **elektrických** a **elektronických zařízení**.

AKTUÁLNÍ PROJEKTY: ODPADY – VODA - OVZDUŠÍ

- Cirkulární ekonomika, inovativní metody a přístupy (ecodesign, LCA, uhlíková a vodní stopa)
- Prevence, materiálové, biologické a energetické využití odpadů
- Průmyslové a komunální odpadní vody, kaly, získávíní fosforu, recyklace vody
- Čištění odpadních plynů a spalin, snižování a měření emisí

ODPADY ZE A PRO STAVEBNICTVÍ

- Udržitelná výstavba
- Efektivní využití surovin a cirkulární ekonomika
- Předcházení vzniku odpadů
- Recyklace a downcyklace
- Využití vedlejších produktů a odpadů z jiných průmyslových odvětví
- Inovativní přístupy a materiály
- Brownfieldy

ODPADNÍ TEXTIL

- Udržitelná textilní výroba a spotřeba
- Možnosti využití použitého textilu
- Bezpečnostní a zdravotní aspekty recyklátů
- PFAS a jejich dopady na životní prostředí
- Uživatelské chování a marketing

OEEZ A ELEKTROPRŮMYSL

- Ecodesign a jeho aplikace
- Postupy demontáže a recyklace
- Získávání a recyklace kritických surovin
- Toxické látky a kontaminované materiály

KLÍČOVÉ TERMÍNY

Přihlášky příspěvků	**30. 6. 2025**
Zaslání plných textů do sborníku	**15. 9. 2025**
Přihlášky účasti	**30. 9. 2025**
Termín konání	**14. – 16. 10. 2025**

CENY VLOŽNÉHO

Plné vložné	**6 500 Kč**
Jednodenní vložné	**5 000 Kč**

PŘIHLÁŠKY PŘÍSPĚVKŮ A PREZENTACE PŘEDNÁŠEK

Příspěvky na TVIP mohou mít povahu přednášky v odborné sekci (15 min. přednáška a 5 min. diskuse) nebo vývěsky. Vývěsky mohou být až do formátu A0 na výšku, větší rozměry je třeba konzultovat s pořadateli.

Termín přihlášek příspěvků je **30. 6. 2025.** Přihlášky je možné zasílat výhradně prostřednictvím elektronického formuláře na **www.tvip.cz**. Pořadatel potvrzuje přijetí přihlášky a vyhrazuje si právo konečného rozhodnutí o přijetí příspěvku, formě jeho prezentace a zařazení do konkrétní sekce a programu.

Po uvedeném datu je možno přihlásit příspěvek buď po výzvě přípravného výboru, nebo do naplnění kapacity (sestavení konečného programu). Jednací jazyk je čeština a slovenština. Zahraniční přednášející (i posluchači) jsou vítáni, ale tlumočení nezajišťujeme. Komerční prezentace na konferenci je možná, více na **www.tvip.cz**.

PLNÉ TEXTY PŘEDNÁŠEK

Autory všech příspěvků, přednášek i vývěsek žádáme o včasné předání konečného, graficky upraveného plného textu příspěvku v elektronické podobě v MS Word nejpozději do **15. 9. 2025**. Požadavky na grafickou úpravu textů do sborníku jsou uvedeny na internetových stránkách TVIP, kde je rovněž i vzorová šablona pro psaní textů. Sborník TVIP je vydáván v elektronické formě s označením ISBN.

PUBLIKACE VE WASTE FORUM

Časopis WASTE FORUM, který je dlouholetým mediálním i odborným garantem TVIP, je od roku 2017 indexován v databázi SCOPUS. V případě zájmu o publikaci příspěvku ze symposia v časopisu je toto možné. Publikační jazyk je angličtina, čeština a slovenština. Redakční uzávěrky jsou pravidelně 8. 1., 8. 4., 8. 7. a 8. 10. Text je třeba upravit podle redakčních zvyklostí (více na www.wasteforum.cz/ v sekci Pro autory). Příspěvky jsou posuzovány minimálně dvěma nezávislými recenzenty. Hotové číslo bývá vystaveno na internetu zhruba 10 – 11 týdnů po redakční uzávěrce. Všechna čísla časopisu (aktuální i archivní) jsou volně ke stažení na stránkách www.wasteforum.cz.

PŘIHLÁŠKY ÚČASTI

K účasti na TVIP se přihlašuje prostřednictvím formuláře na **www.tvip.cz**. Jeho součástí je i specifikace objednávaného ubytování a rozsahu stravování. Bližší informace na stránkách internetu. **Termín pro přihlášení je 30. 9. 2025** K účasti se přihlašují (a platí vložné) i autoři příspěvků, přednášky nejsou honorované. Za neodpřednášenou přednášku či za nevystavený poster fakturujeme poplatek 1000 Kč za zařazení příspěvku do programu a uveřejnění textu ve sborníku.

DRUHÝ CIRKULÁŘ A DALŠÍ INFORMACE

Druhý cirkulář s předběžným programem bude rozesílán v polovině září. Veškeré, průběžně aktualizované informace k TVIP naleznete na internetových stránkách **www.tvip.cz**. Konkrétní dotazy a připomínky adresujte buď na níže uvedené garanty, nebo na společnou adresu **tvip@cemc.cz**.

POŘADATEL

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IČO: 45249741, DIČ: CZ45249741
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