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Teknologi Pencegahan Pencemaran Industri

Volume 14 Special Issue, December 2023

FOCUS AND SCOPE

Jurnal Riset Teknologi Pencegahan Pencemaran Industri (Research Journal of Industrial Pollution Prevention Technology) seeks to promote and disseminate original research as well as review, related to following area:

Environmental Technology : within the area of air pollution technology, wastewater treatment technology, and management of solid waste and harzardous toxic substance.

Process Technology and Simulation : technology and/or simulation in industrial production process aims to minimize waste and environmental degradation.

Design Engineering : device engineering to improve process efficiency, measurement accuracy and to detect pollutant.

Material Fabrication : environmental friendly material fabrication as subtitution material for industry.

Energy Conservation : process engineering/ technology/ conservation of resources for energy generation.

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Jurnal Riset

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PREFACE

Thanks to Allah, the Most Gracious and Most Merciful, the Journal of Industrial Pollution Prevention Technology (JRTPPI) has published its 14th volume, special issue. This journal contains scientific articles, particularly in the fields of environmental technology, process technology and simulation, design engineering, material fabrication, and energy conservation. We would like to express our sincere appreciation to the head of the Center for Standardization and Industrial Pollution Prevention Services, Ministry of Industry, for their continuous support of JRTPPI. We also extend our gratitude to the authors, editorial board, and reviewers who have actively participated in maintaining the consistency of quality and timely publication.

This edition consists of six full-text English scientific articles. This is part of the editorial board's commitment to improving the authors' performance in delivering the results of their research and making it easily accessible to a broader audience to increase the number of citations. This policy is also aimed at realizing our goal of JRTPPI being a globally indexed international journal.

The articles in this edition include isotherm study, adsorption kinetics and thermodynamics of lead using combination adsorbent of chitosan and coffee ground activated carbon, the processing of LDPE plastic waste into renewable fuel using waste motor oil, global context of industry 5.0 : current trends and challenges in Indonesia, synthesis of silica nanoparticle made from Lampung pumice modified with sonication parameters for size and purity, tempeh industry wastewater treatment using mix natural adsorbents (zeolite, bentonite, water hyacinth-activated carbon): effect of mass ratio and dosage of mix adsorbents on turbidity and pH, and transforming the furniture industry in the digital age. These six manuscripts were accepted and published in this edition from researchers and lecturers in Indonesia. The submission, review, and editing process for these manuscripts ranged from 1 to 6 months.

Hopefully, these scientific articles will provide new knowledge and experiences for readers in academia, researcher, industry, community and society at large. We realize that nothing is perfect until all parties have continuously improved.

Semarang, December 2023

Chief Editor

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ABSTRACT

Published on December 22, 2023

Nisa Nurhidayanti*[1], Aris Dwi Cahyanto[1]

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Isotherm Study, Adsorption Kinetics and Thermodynamics of Lead Using Combination Adsorbent of Chitosan and Coffee Ground Activated Carbon

Jurnal Riset Teknologi Pencegahan Pencemaran Industri, December 2023, Vol. 14, Special Issue, p. 1-11, 11 ill, 2 tab, 25 ref

The presence of lead metal in water naturally, due to its mobility, can cause the nature of water to become toxic and endanger the environmental ecosystem by causing bioaccumulation within the food chain. The purpose of this study was to determine the maximum adsorption capacity through an isotherm model, ascertain the rate of adsorption kinetics when utilizing chitosan and coffee grounds as adsorbents to reduce lead concentrations in industrial wastewater, and analyze its thermodynamic properties. The research method was carried out using experiments in the laboratory followed by quantitative data analysis to determine the isotherm model and adsorption kinetics. The results showed that the adsorption isotherm conforms to the Langmuir isotherm model with a correlation coefficient of 0.9970 with a maximum adsorption capacity of 1.0511 $mg.g^{-1}$ which indicates that chemical adsorption occurs in the mono layer with a homogeneous distribution of adsorption sites with adsorption energy constant, with negligible interactions between lead metal molecules (adsorbate). The kinetics of lead adsorption using chitosan-activated carbon coffee grounds following the Weber-Morris/intra-particle diffusion model with a correlation coefficient of 0.9920 with a diffusion rate of 76.512 $g.mg^{-1}.hour^{-1}$ indicating that intra-particle diffusion is the rate step limiting in the overall biosorption process. Negative ΔG^o values indicate that the adsorption reaction takes place spontaneously, ΔH^o of 0.8130 indicates an endothermic reaction, and ΔS^o of 4.1888 indicates an increase in the randomness of the adsorption process at the adsorbent interface and lead during adsorption.

(Author)

Keywords: Chitosan, Coffee Ground, Isotherm, Kinetics, Lead, Thermodynamics

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The Processing of LDPE Plastic Waste into Renewable Fuel Using Waste Motor Oil

Jurnal Riset Teknologi Pencegahan Pencemaran Industri, December 2023, Vol. 14, Special Issue, p. 12-20, 8 ill, 0 tab, 33 ref

The increase in population causes an increasing amount of solid waste, especially plastic waste. Plastic waste that cannot be decomposed in nature increases its number and causes environmental pollution. This research aimed to process plastic waste into alternative fuel oil using waste motor oil. The research methods consisted of designing a plastic waste processing device using waste motor oil as fuel and testing the device with a plastic burning process using a processing machine. The plastic waste processing device was produced as a stove to heat plastic waste fueled by waste motor oil using an electric blower to generate pressure into the reactor. The heating process produces steam flowing and processing in a distillation tube to produce oil. LDPE plastic waste could produce renewable fuel at the temperature of 140°C, but there were still burning residues. The distillation produced two types of fuel oil, yellow and black.

(Author)

Keywords: Plastic Waste, Oil Waste, Processing Machines, Renewable Fuel

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Global Context of Industry 5.0 : Current Trends and Challenges in Indonesia

Jurnal Riset Teknologi Pencegahan Pencemaran Industri, December 2023, Vol. 14, Special Issue, p. 21-32, 2 ill, 5 tab, 25 ref

This article reviews the strategies and potential implications of implementing Industry 5.0 in Indonesia, emphasizing environmental impact, process technology, and energy conservation. To provide a comprehensive understanding of Indonesia's challenges and opportunities in transitioning to Industry 5.0 and to elucidate the impact of this shift on environmental sustainability, technological processes, and energy efficiency. An in-depth analysis was conducted on current technological trends, such as 3D printing, augmented reality, virtual reality, IoT, and AI, and their potential roles in the Indonesian industrial sector. We also explored the infrastructural needs, the significance of a skilled workforce, and the regulatory framework essential for a seamless transition. Findings highlight the critical importance of human-centric manufacturing, the potential benefits of Industry 5.0 technologies for environmental and energy efficiency, and the need for robust collaborations among government, industry, and research institutions for a successful transition. Recommendations emphasize infrastructure development, human resource enhancement, supportive policies, and multi-sectoral collaboration.

(Author)

Keywords: Collaboration, Energy Conservation, Environmental Impact, Industry 5.0, Process Technology

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Synthesis of Silica Nanoparticle Made from Lampung Pumice Modified with Sonication Parameters for Size and Purity

Jurnal Riset Teknologi Pencegahan Pencemaran Industri, December 2023, Vol. 14, Special Issue, p. 33-40, 5 ill, 7 tab, 21 ref

Silica nanoparticles are widely utilized nanomaterials in various industries due to their unique characteristics. Homogeneous nanoscale size is preferred to obtain superior properties. This research was conducted to determine the sonication parameters of pumice rock synthesis on silica size and purity formation. Silica synthesis was carried out until a white gel formed, followed by sonication at temperatures of 30°C, 60°C, and 80°C for 1, 2, and 3 hours. The purity of silica was analyzed through X-ray fluorescence results, X-ray diffraction, and SEM imaging for morphology analysis. The synthesis results followed by the sonication process had the highest SiO_2 concentration of 98.97%. The sonication temperature had a significant effect and contributed 67.25%, higher than the sonication time of 22.4%. The highest SiO_2 concentration of >98% was achieved at 40ºC for 1.5 hrs. Meanwhile, for particle size, both parameters have a significant effect with an error value of α: 3.14%. Particle size <6 nm was obtained with a sonication temperature of 50ºC for 2 hours. The sonication process can increase the concentration and reduce the size of the synthesized silica particles by selecting appropriate independent variables.

(Author)

Keywords: ANOVA, Pumice, Silica, Sol Gel, Sonication, Synthesis, Taguchi

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Tempeh Industry Wastewater Treatment using Mix Natural Adsorbents (Zeolite, Bentonite, Water Hyacinth-Activated Carbon): Effect of Mass Ratio and Dosage of Mix Adsorbents on Turbidity and pH

Jurnal Riset Teknologi Pencegahan Pencemaran Industri, December 2023, Vol. 14, Special Issue, p. 41-52, 6 ill, 1 tab, 32 ref

Adsorption is the agglomeration of dissolved substances in solution by the surface of an absorbent substance, making the material enter and collect in an absorbent substance. Natural adsorbents that treat tempeh wastewater are mixed adsorbents that consist of zeolite, bentonite, and activated carbon made from water hyacinth. This study aimed to determine the effect of the mass ratio and dose of mixed natural adsorbents on tempeh wastewater's turbidity and pH values and the isotherm that occurred. The mass ratio variation used was the ratio of each material in the form of zeolite: bentonite: activated carbon in the form of R1 (1:1:1), R2 (2:1:1), R3 (1:2:1) and R4 (1:1:2). The adsorbent dose carried out was 1.5 gr; 3 grams; and 4.5 gr per 100 ml volume of wastewater. The contact time between the adsorbent and the wastewater is every 15, 30, 60, 90, 120, 150 minutes. Tempeh wastewater was processed in laboratory-scale batches with 120 rpm stirring. The primary analysis carried out is turbidity and pH. The results showed that the adsorption reduced turbidity and increased the pH level by processing the mass ratio R2 (2:1:1) for 150 minutes with a dose of 4.5 grams. It was found that the turbidity decreased by 99.5% from 520.5 NTU to 2.47 NTU, and the pH level increased from 3.7 to 6.4 after processing for 150 minutes at a dose of 4.5 grams. The maximum adsorption capacity validation results were obtained based on the Langmuir analysis of 8.26-10.61 mg/g with a constant of 0.27-6.4. These results show that mixed natural adsorbent is effective and potentially develops on tempeh wastewater treatment.

(Author)

Keywords: Activated carbon, Adsorption, Bentonite, pH, Tempe Wastewater, Turbidity, Zeolite

Rame*[1,2], Purwanto[2,3], Sudarno[2,4]

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Transforming The Furniture Industry in The Digital Age

Jurnal Riset Teknologi Pencegahan Pencemaran Industri, December 2023, Vol. 14, Special Issue, p. 53-69, 2 ill, 0 tab, 51 ref

The furniture industry is experiencing a significant transition driven by digital technologies. This article comprehensively reviews various technologies, techniques, and innovations the furniture industry adopts to enhance efficiency, sustainability, and competitiveness. The analysis draws on a systematic literature review of recent publications in ScienceDirect and Scopus databases. The study highlights the potential of automation, robots, augmented reality, and the Internet of Things to improve the furniture production process, reduce waste, and boost profitability. Additionally, the article examines technologies and approaches that can help the furniture industry become more sustainable and socially responsible, such as green supply chain management, life cycle assessment, and ergonomic treatments. The paper concludes by advocating for a comprehensive digital transformation strategy that includes embracing new technologies, developing innovative business models, and promoting sustainability and ethical standards.

(Author)

Keywords: Automation, Digital Transformation, Furniture Industry, Life Cycle Assessment, Sustainability

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Isotherm Study, Adsorption Kinetics and Thermodynamics of Lead Using Combination Adsorbent of Chitosan and Coffee Ground Activated Carbon

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ABSTRACT

The presence of lead metal in water naturally, due to its mobility, can cause the nature of water to become toxic and endanger the environmental ecosystem by causing bioaccumulation within the food chain. The purpose of this study was to determine the maximum adsorption capacity through an isotherm model, ascertain the rate of adsorption kinetics when utilizing chitosan and coffee grounds as adsorbents to reduce lead concentrations in industrial wastewater, and analyze its thermodynamic properties. The research method was carried out using experiments in the laboratory followed by quantitative data analysis to determine the isotherm model and adsorption kinetics. The results showed that the adsorption isotherm conforms to the Langmuir isotherm model with a correlation coefficient of 0.9970 with a maximum adsorption capacity of 1.0511 $mg.g^{-1}$ which indicates that chemical adsorption occurs in the mono layer with a homogeneous distribution of adsorption sites with adsorption energy constant, with negligible interactions between lead metal molecules (adsorbate). The kinetics of lead adsorption using chitosan-activated carbon coffee grounds following the Weber-Morris/intra-particle diffusion model with a correlation coefficient of 0.9920 with a diffusion rate of 76.512 $g.mg^{-1}.hour^{-1}$ indicating that intra-particle diffusion is the rate step limiting in the overall biosorption process. Negative ΔG^o values indicate that the adsorption reaction takes place spontaneously, ΔH^o of 0.8130 indicates an endothermic reaction, and ΔS^o of 4.1888 indicates an increase in the randomness of the adsorption process at the adsorbent interface and lead during adsorption.

1. INTRODUCTION

Bekasi Regency is Southeast Asia's largest industrial zone. A preliminary study conducted on a wastewater sample from one of textile industries in the Bekasi district showed a lead metal concentration of 1.02 mg/L. Notably, this concentration of lead metal exceeds the water quality standard limit concentration of 0.1 mg/L as outlined in the 2014 Waste Water Quality Standard Environment Ministry Ordinance Number 5 (Ministry of Environment, 2014). Lead (Pb) is a heavy metal commonly encountered in effluents originating from electronics and silicon semiconductor industries, primarily due to its prevalence as a constituent in these materials. The high concentration of lead in these industries can result in its release into the environment. Lead exhibits natural mobility and can be distributed through various means, including chemical reactions, biological processes, geochemical interactions, volcanic activities, and human activities. Because lead metal is naturally present in water due to its mobility, the toxic nature of the water made it a problem all over the world from the 20th century to his 21st century. With a density of 11.400 kg/m^3, lead is a heavy metal found in nature and typically occurs in the form of bluish minerals alongside elements like oxygen and sulfur. Due to its toxic

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characteristics, lead is recognized as a hazardous metal that can lead to neurocognitive impairments. This is attributed to factors such as its lethal dosage, assimilation rate, and half-life within the human body (M. S. Kim et al., 2014).

Various methods, including chemical precipitation, adsorption, membrane filtration, ion exchange, and coagulation-flocculation, are employed to mitigate the presence of heavy metals in wastewater. Recent research efforts have primarily focused on exploring alternative adsorbents that not only offer cost-effectiveness but also exhibit environmentally friendly attributes, characterized by their ease of operation and high efficiency (H. Kim, Hwang, & Sharma, 2014). Chitosan (β-1,4,2-amino-2-deoxy D-glucose) is an organic material derived from chitin obtained through a deacetylation process at high temperatures using a strong base (Nuryono et al., 2020). Chitosan has been used as an adsorbent to reduce heavy metals, but it has the disadvantage of increasing water turbidity, requiring further treatment. Combining chitosan and coffee grounds increases the recyclability of the sorbent, improves the chemical stability and adsorption capacity of the sorbent, and improves the reduction efficiency (Das, Chakraborty, Chatterjee, & Kumar, 2018). The utilization of chitosan and activated carbon derived from coffee grounds as adsorbents has demonstrated effective reduction capabilities for various heavy metals. For instance, cadmium levels were reduced by 74.54%, and nickel levels by 73.43% (Purnama, 2019). Additionally, these adsorbents have been found to efficiently reduce lead metal, achieving an adsorption efficiency of 92.26% and resulting in a final concentration of 0.774 mg/L within a contact time of 120 minutes (Said, 2018). Furthermore, these materials have also been successful in reducing drug contaminants present in wastewater, including metamizole, acetyl salicylic acid, acetaminophen, and caffeine (Lessa, Nunes, & Fajardo, 2018).

A previous study demonstrated that the reduction of lead concentration in industrial wastewater using natural chitosan and activated carbon from coffee grounds as sorbents resulted in a reduction of 90.86%, yielding a final concentration of 0.09 mg/L (Nurhidayanti, Ilyas, & Suwazan, 2021). Previous research has explored the isothermal model and reaction kinetics of metallic arsenic reduction (Nurhidayanti & Nugraha, 2022), as well as the reaction kinetic analysis and adsorption isotherms of chicken egg shells, membranes, and synthetic dyes (Hevira & Gampito, 2022). However, the proper lead metal adsorption isotherm model has not been studied to determine the adsorption capacity of the use of chitosan and coffee grounds adsorbents in reducing lead concentrations in industrial wastewater (Nurhidayanti et al., 2021; Suwazan & Nurhidayanti, 2022; Suwazan, Nurhidayanti, Fahmi, & Riyadi, 2022). The purpose of this study is to explore the maximum adsorption capacity through an isotherm model, to determine the rate of adsorption kinetics in the use of chitosan and coffee grounds adsorbents in reducing lead concentrations in industrial wastewater, and to investigate its thermodynamic ascpects.

2. METHODS

This study was conducted at PT. Tuv Nord Indonesia and Pelita Bangsa University from June to December 2022. The research employed laboratory experiments followed by quantitative data analysis to determine isothermal models, adsorption kinetics, and thermodynamics. The materials utilized in this study included chitosan, $ZnCl_2$ p.a solution 0.1 N (Merck), HCl p.a solution 0.1 N (Merck), NaOH p.a solution 0.1 N (Merck), lead stock solution 1000 mg/L, and coffee grounds obtained from coffee shops as waste. The tools employed for this study comprised beakers, an analytical balance, filter paper, volume pipette, funnel, porcelain cup, universal indicator, oven, spatula, acrylic plate, hot plate, sieve, furnace, desiccator, rubber suction/bulb, aluminum foil, ball mill, magnetic stirrer, vacuum, Fourier Transform-Infrared (FT-IR) Perkin-Elmer UATR Spectrum Two, and Scanning Electron Microscopy-Energy Dispersive X-Ray (SEM-EDX) JEOL JSM-6510LA. The Research procedure in this study follows the flowchart as presented in Figure 1.

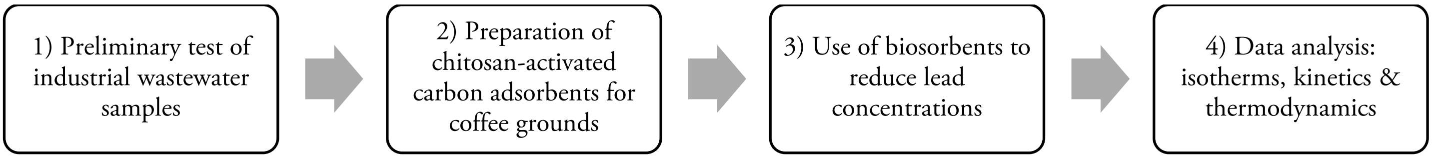


Figure 1. Research procedure

The research process from stages 1 to 3 has been carried out in 2021 (Nurhidayanti et al., 2021). The operational conditions employed included pH control, mass variation ranging from 0.6 to 1.4 grams, activated carbon particle size of 160 mesh, initial lead concentration of 1.02 mg/L, stirring speed of 100 rpm, contact time spanning from 5 to 25 minutes, and a temperature range of 25 to 55°C. The scope of this research is at point 4 of the framework in the picture above. The isotherm models used in this study are Langmuir, Freundlich, Dubinin Raduskevich (D-R) and Temkin isotherms. Determination of the adsorption capacity (q) uses equation 1 (Sunsandee, Ramakul, Phatanasri, & Pancharoen, 2020).

$$q = \frac{(C_i - C_t) x\, V}{m} \quad (1)$$

Where q is biosorption capacities (mg/g), Ci is the initial concentration of lead (mg/L), Ct is the concentration of lead at time t (mg/L), V is volume of lead solution, and m is mass of adsorbent used in the reaction mixture (g).

Data analysis was performed using final lead concentration data that underwent an adsorption process using the adsorbent chitosan charcoal coffee powder with mass change (from 0.6 grams to 1.4 grams) to obtain the maximum adsorption capacity. The results of this analysis are reflected in the isotherm equations.

Biosorption equilibrium data were fitted to linear Langmuir, Freundlich, Temkin, and Dubinin-Raduskevich isotherms (D-R). The Langmuir isotherm equation has the nonlinear form (Wang & Guo, 2020a):

$$\frac{C_e}{q_e} = \frac{C_e}{q_m} + \frac{1}{K_L q_m} \quad (2)$$

where q_e is the equilibrium biosorption capacity (mg/g), C_e is the concentration of at equilibrium (mg/l), qm is the maximum biosorption capacity (mg/g) and KL is the Langmuir equation constants (L/mg) that can to be determined by $\frac{C_e}{q_e}$ vs based on the linear plot of C_e. The Freundlich isotherm equation has the following non-linear forms (Wang & Guo, 2020a):

$$\log q_e = \log K_F + \frac{1}{n} \log C_e \quad (3)$$

Where KF is the Freundlich constant, and 1/n is the biosorption intensity. The value 1/n < 0 indicates the reaction takes place irreversible. If 0 < 1/n < 1, the biosorption reaction is desired, while if 1/n > 1, the biosorption reaction is not desired. Plotting C_e versus Q_e can solve the Freundlich model in equation (3). The determination of KF and qm is generated from the slope and intercept resulting from the regression equation. This D-R isotherm model is expressed by the following equation (Wang & Guo, 2020a):

$$q_e = q_{mD-R} e^{-K_{DR}\, \varepsilon^2} \quad (4)$$

$$\varepsilon = RT \ln(1 + \frac{1}{C_e}) \quad (5)$$

Where q_{mD-R} (mg/g) is the maximum biosorption capacity; 〚$-K_{DR}$ is the activity coefficient (mol^2/J^2); Ɛ (kJ/mol) is the biosorption potential based on Polanyi potential theory. The Temkin isotherm model is expressed in the following equation (Wang & Guo, 2020a):

$$q_e = \frac{RT}{b} \ln(AC_e) \quad (6)$$

Where R is the universal gas constant, T is the temperature; A (L/g) is the equilibrium constant and b (J/mol) is the Temkin constant related to the heat of biosorption.

To investigate the mechanism of the adsorption process, pseudo-first-order adsorption, pseudo-second-order adsorption models, Elovich and Webber Morris were used to test the adsorption data. The pseudo-first-order model (Wang & Guo, 2020b) is expressed by Equation (7):

$$\ln(q_e - q_t) = \ln(q_t) - k_1 t \quad (7)$$

where qe is equilibrium biosorption capacities (mg/g) and qt is the amounts of lead adsorbed on the adsorbent at time (mg/g), t is time, and k1 is the pseudo-first-order rate constants (min-1)

The pseudo second-order index model (Wang & Guo, 2020b) is given in Eq. (8):

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e} t \qquad (8)$$

where k2 is the constant of the pseudo-second-order rate (g/mg/min), which is obtained by plotting $\frac{t}{q_t}$ versus t.

The Elovich model has been expressed in Equation (9):

$$q_t = \frac{1}{b} \ln (ab) + \frac{1}{b} \ln (t) \qquad (9)$$

Then a graph of the relationship q_t versus ln t is made which will produce slope as a value of 1/b and an intercept as a value of 1/b ln (ab).

The Webber Morris model has been expressed in Equation (10):

$$q_t = k_i t^{1/2} \qquad (10)$$

Where ki is the intra-particle diffusion constant. Then graph the relationship between q_t versus $t^{1/2}$ which will produce the slope as the value of ki.

Determination of the appropriate isotherm model and adsorption kinetics was carried out based on the correlation coefficient with the largest R^2 value close to 1.0 using Microsoft excel software.

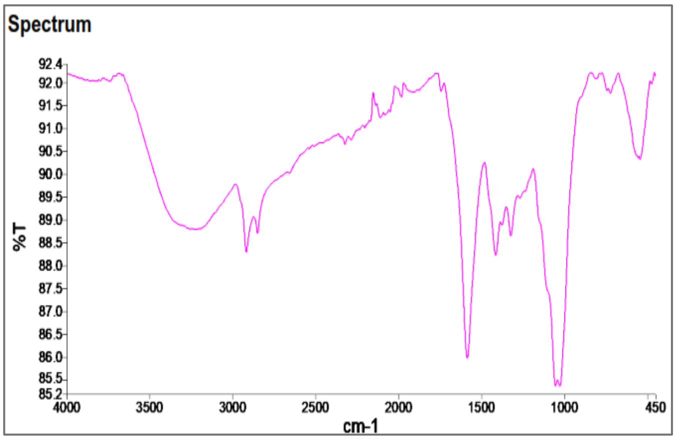
The thermodynamic behavior of the biosorption of lead on adsorbent can be described by the thermodynamic parameters, including the change in free energy (ΔG°), enthalpy (ΔH°) and entropy (ΔS°), which were calculated based on the following equation (Sunsandee et al., 2020).

$$\Delta G^\circ = -RT \ln Keq \qquad (11)$$

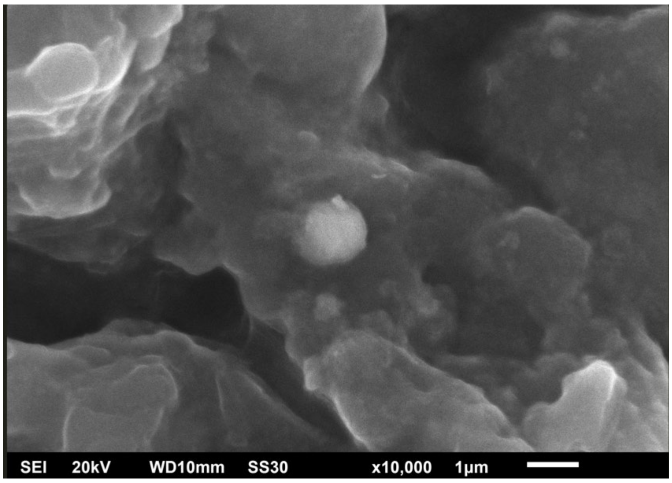
Where R is the universal gas constant (8.314 J/mol K), T is the temperature (K) and K_D is the equilibrium constant.

3. RESULTS AND DISCUSSION

The results of the FT-IR and SEM-EDX analysis with operating conditions pH, mass variation of 0.6-1.4 gram, activated carbon particle size of 160 mesh, the ratio of chitosan activated carbon and coffee grounds is 50:50 , initial lead concentration of 1.02 mg/L, stirring speed (100 rpm), contact time of 5-25 minutes, and the temperature used 25-55°C are presented in Figures 2a and 2b.



(a)



(b)

Figure 2. a) Results of FT-IR spectrum and b) SEM-EDX from biosorbent

The FT-IR analysis result showed the presence of various functional group in the biosorbent, including CH (as an alkane), NH (possibly as a secondary/primary amine and amide), N=O (nitro), CO (possibly as an alcohol/ether/ester/carboxylic acid/ anhydride), CN (amine) C-Cl (chloride), and N=O (nitro). This indicates that the interaction between activated carbon from coffee and chitosan involves both physical interaction and a chemical reaction that results in the formation of a nitro group (NO_2) in the activated carbon made from coffee grounds as part of the chitosan biosorbent. The introduction of the nitro functional group enhances adsorption capacity due to electrostatic interaction with lead metal cations, thereby increasing the adsorption ability of the chitosan-activated carbon composite (Nurhidayanti, Ilyas, Suwazan, & Fajar, 2022). The results of SEM-EDX consistent with previous research that adding activated carbon from coffee grounds to chitosan can improve the biosorbent active site and open up more surface pores, which increasing the absorption of cadmium and lead metals in PXI industrial effluent (Sahu, Singh, & Koduru, 2021). In comparison to using chitosan adsorbent or coffee grounds activated carbon individually, the combination of the two is more efficiently employed as an adsorbent due to the increase in pore size and quality of the adsorbent. The adsorption capacity of an adsorbent is positively correlated with its surface area, signifying greater efficiency in adsorbing target contaminants (Joshi, Kataria, Garg, & Kadirvelu, 2020).

The use of chitosan coffee grounds sorbent to reduce lead concentrations in industrial wastewater is shown in Figure 3.

The figure above shows that the highest reduction in lead metal concentration was in the use of chitosan adsorbent with a coffee grounds activated carbon mass of 1.4 grams to 0.09 mg/L. This implies that as the mass of coffee grounds activated carbon, in conjunction with chitosan, increases during the adsorption process, there is a corresponding enhancement in the reduction of lead concentration. This correlation can be attributed to the amplified adsorption capacity, which is directly proportional to the augmented active absorption sites on the biosorbents. The increased mass of activated carbon consequently leads to a higher potential for the removal of lead metal from wastewater due to the heightened availability of active sites for adsorption (Naga Babu, Reddy, Kumar, Ravindhranath, & Krishna Mohan, 2018).

Table 1. Parameters of lead adsorption isotherm using chitosan-activated carbon of coffee grounds

No.	Langmuir	Freundlich	Dubinin-Raduskevich	Temkin
1	K_L=40.204	K_F=0.1869	q_{mD-R}=3.7123	b_T=0.0057
2	Q_m=1.0511	1/n=-3.8425	ε=8x10^{-9}	B=0.0199
3	R_L=2.3805	R^2=0.9732	R^2=0.9433	R^2=0.9815
4	R^2=0.9970			

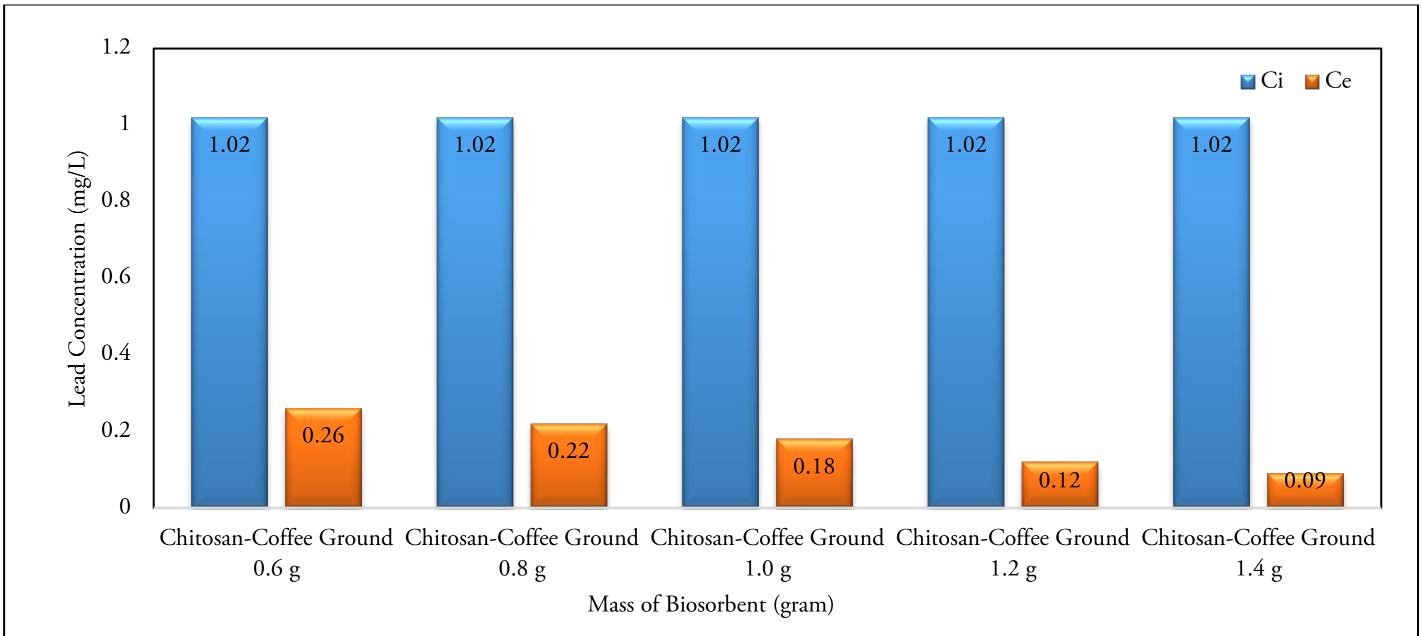


Figure 3. Reduction in lead concentration at various concentrations of biosorbents

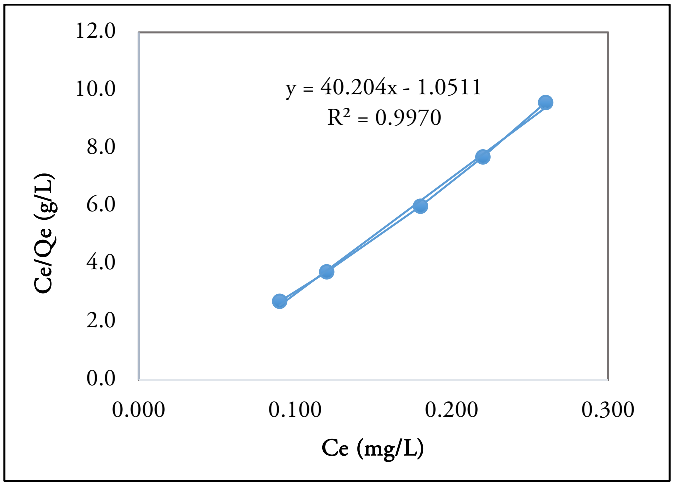


Figure 4. Plot Ce vs Ce/Qe on the Langmuir isotherm model

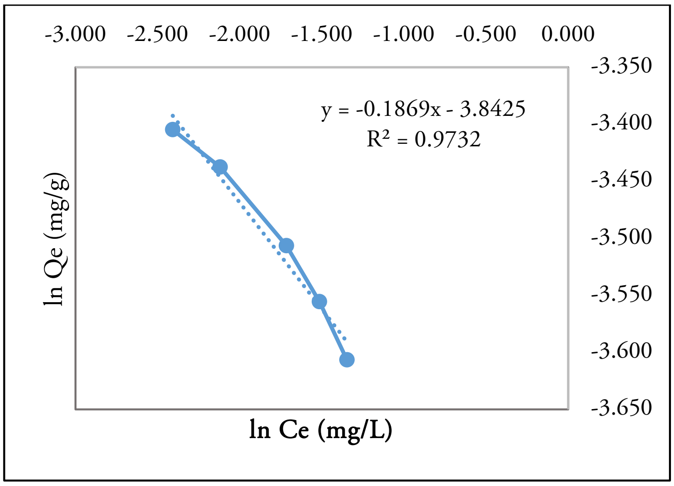


Figure 5. Plot Ln Ce vs Ln Qe on the Freundlich isotherm model

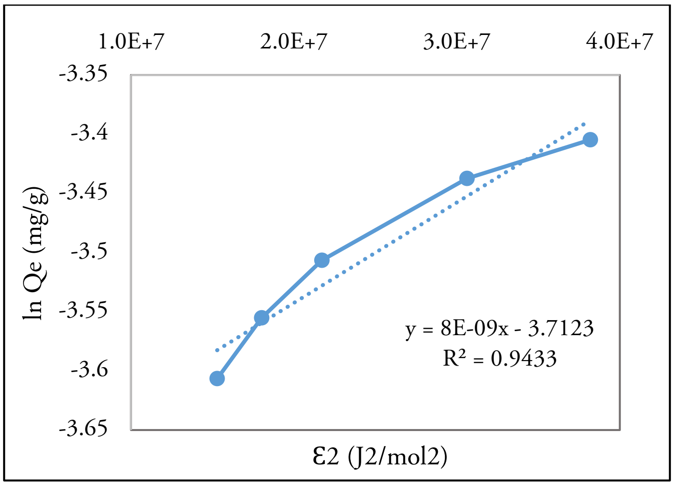


Figure 6. Plot Ce vs Ce/Qe on the Dubinin-Raduskevich (D-R) isotherm model

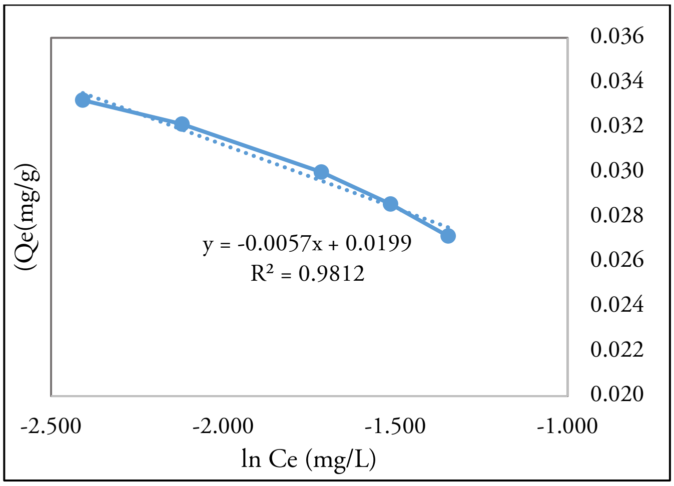


Figure 7. Plot Ln Ce vs Qe on the Temkin isotherm model

The results of data analysis performed using Microsoft Excel on several isotherm equations are presented in Figures 4 to 7.

The figure above shows that the correct isotherm model for the adsorption process of lead metal using chitosan-activated carbon coffee grounds is the Langmuir model because the highest correlation coefficient is 0.9970. This is later followed by the models of Temkin, Freundlich and Dubinin-Raduskevich. The magnitude of the adsorption isotherm parameters is presented in Table 1.

The table above shows the calculated data regarding several adsorption isotherm parameters, namely the Langmuir constant which is 40.204 with a maximum adsorption capacity of 1.0511 mg/g and a separation factor (RL) value of 2.3805 which means that adsorption is favorable (RL>1) (Khalil et al., 2020). The Freundlich equation shows that there is a Freundlich constant (KF) of 0.1869 and a biosorption intensity (1/n) of -3.8425 (<0), which means that the adsorption reaction takes place in irreversible (Pagalan et al., 2020). Consequently, it is feasible to conclude that the significant lead adsorption on biosorbent that has been chemically activated by phosphoric acid verifies the presence of enhanced porosity and a high specific surface. The laboratory-produced active carbon has a strong affinity for this heavy metal. (Benyekkou, Ghezzar, Abdelmalek, & Addou, 2020).

The Dubinin Raduskevich isotherm equation shows that there is a maximum adsorption capacity ($q_{mD\text{-}R}$)

of 3.7123 $mg.g^{-1}$, the biosorption potential based on Polanyi potential theory (ε) is $8x10^{-9}$ kJ/mol. The Temkin isotherm equation shows that the Temkin constant associated with the heat of biosorption is 0.0199 J/mol. In this equation, bT is referred to as the Temkin harmony constant, which is linked to the highest binding energy. On the other hand, B is essential to characterize the heat of adsorption. The Temkin constant, denoted as b, is associated with the heat of adsorption measured in kJ/mol. As per the Temkin adsorption isotherm, direct fittings were achieved by plotting qe against ln Ce at the experimental temperatures (RT–298K), as depicted in Figure 6. These linear relationships facilitate the examination of the Temkin adsorption isotherm parameters bT and B. The overall heat of adsorption diminishes with an increase in adsorption due to the interaction between lead and the adsorbent surface. The values of the Temkin adsorption constants bT, B, and R2 are presented in Table 1. According to the data extracted from the fittings and included in Table 1, it is evident that the Temkin adsorption isotherm model aligns well in comparison to the Freundlich and Dubinin Raduskevich isotherm models (Sultana et al., 2022).

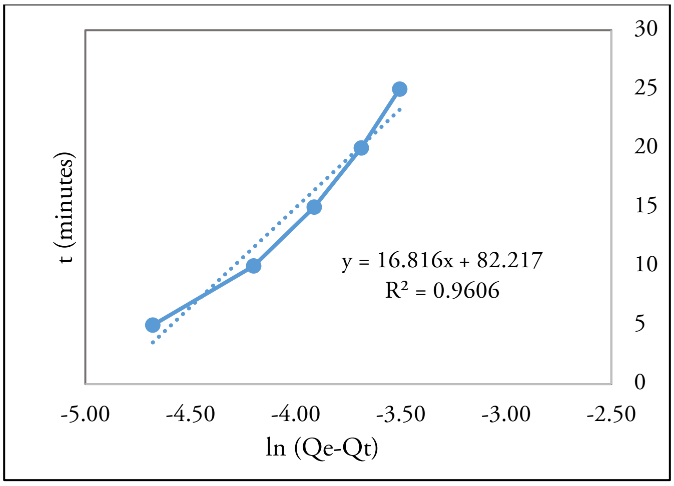


Figure 8. Plot ln(Qe-Qt) vs t on the PFO kinetics model

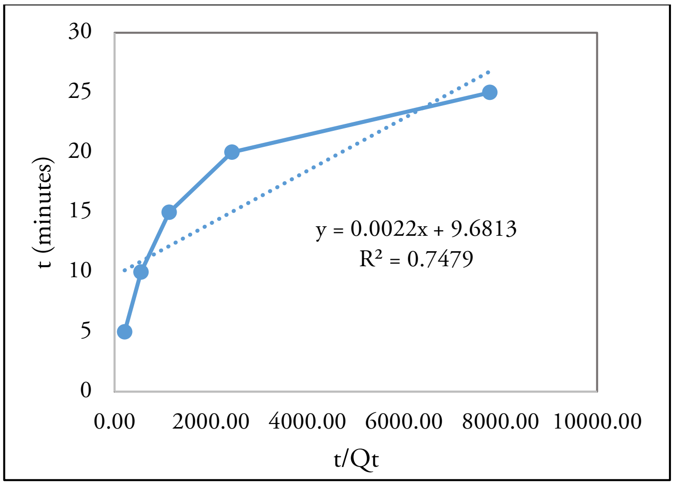


Figure 9. Plot t/Qt vs t on the PSO kinetics model

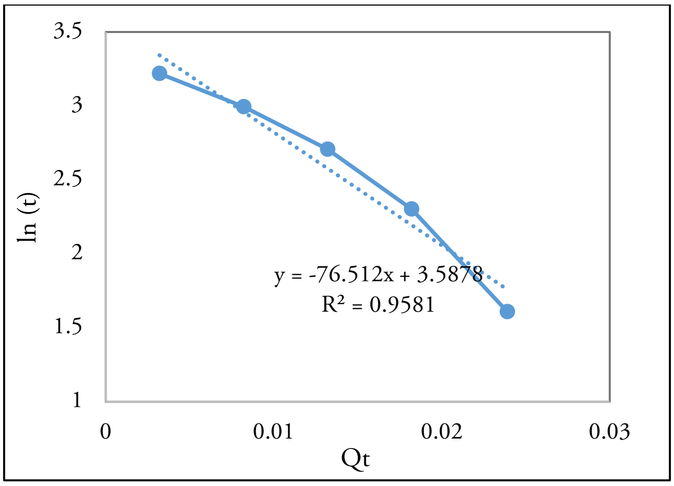


Figure 10. Plot Qt vs Ln t on the Elovich kinetics

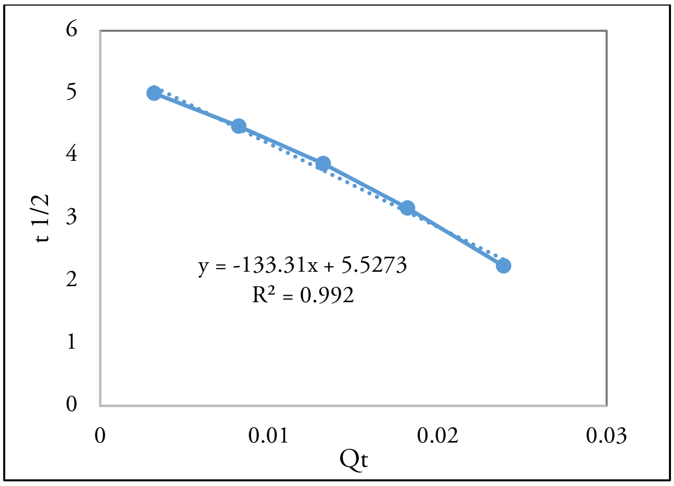


Figure 11. Plot Qt vs t1/2 on the Webber Morris kinetics model model

Based on the data analysis carried out, the correlation coefficient of the Langmuir model> Temkin> Freundlich> Dubinin Raduskevich. This shows that the adsorption isotherm follows the Langmuir isotherm model with a correlation coefficient of 0.9970 with a maximum adsorption capacity of 1.0511 $mg.g^{-1}$ which indicates that chemical adsorption occurs in the mono layer with a homogeneous distribution of adsorption sites with adsorption energy. constant and negligible interactions between lead metal molecules (adsorbate).

The results of data analysis performed using Microsoft Excel on several kinetics equations are presented in Figures 8 to 11.

The magnitude of the adsorption kinetics parameters is presented in Table 2.

The table above shows the calculated data regarding several adsorption kinetic parameters, namely the PFO constant of 82.217 $mg.g^{-1}$ with an adsorption capacity based on weight at equilibrium of 16.816 $mg.g^{-1}$. The PSO equation shows that there is a PSO constant of 9.6813 $mg.g^{-1}.hour^{-1}$ with an adsorption capacity based on weight at equilibrium of 0.0022 $mg.g^{-1}$. The Elovich equation shows that there is an Elovich constant of 76.512 $mg.g^{-1}$. The intra-particle diffusion equation shows the Weber Morris constant of 133.31 $mg.g^{-1}$. By plotting Q_t against $t^{1/2}$ a straight line was found as displayed in Fig. 11 and the magnitudes of k and q_e were estimated from the intercept and slope of the straight line, respectively. The calculated values of q_e, C and R^2 are displayed in Table 2. The constant, k was found to be 133.31 $mg.g^{-1}$ which indicates that the boundary layer thickness is inversely proportional to the internal mass transfer possibility (Sultana et al., 2022). However, the probability of the internal mass transfer is increased with the increase of the boundary layer. The correlation coefficient factor (R^2) is measured as 0.9920 which reveals that the adsorption rate kinetics is an intra–particle diffusion process. The rate constant (k_i) is 76.512 $g.mg^{-1}.h^{-1}$ and the linear form of the plot indicates that the as developed chitosan and coffee grounds adsorbent is suitable for the uptake of the lead from the aqueous solution. Based on the data analysis conducted, the correlation coefficient for the kinetic model of intra-particle diffusion is greater than that of PFO, Elovich, and PSO. This suggests that the adsorption kinetics follow the intra-particle diffusion kinetics model, with a correlation coefficient of 0.9920 and a diffusion rate of 76.512 $g.mg^{-1}.h^{-1}$. This indicates that intra-particle diffusion is the rate-limiting step in the overall biosorption process and is influenced by the biosorption half-life obtained under these conditions (Park et al., 2019).

Negative ΔG^o values indicate that the adsorption reaction takes place spontaneously, ΔH^o of 0.8130 indicates an endothermic reaction, and ΔS^o of 4.1888 indicates an increase in the randomness of the adsorption process at the adsorbent interface and lead during adsorption.

Table 2. The results of rate constant investigated

No	Kinetics Model	Equation	k	q_e	R^2
1	Pseudo First Order (PFO)	$\ln(q_e - q_t) = \ln\ q_e - k_1 t$ Rate = $k_1 (q_e - q_t)$	k_1= 82.217 h^{-1}	16.816 $mg.g^{-1}$	0.9606
2	Pseudo Second Order (PSO)	$\frac{t}{q_t} = \frac{1}{k_2\, q_e^2} + \frac{t}{q_e}$ Rate= $k_2(q_e - q_t)^2$	k_2=9.6813 $g.mg^{-1}.h^{-1}$	0.0022 $mg.g^{-1}$	0.7479
3	Elovich	$q_t = \frac{1}{b}\ln(ab) + \frac{1}{b}\ln(t)$ $Rate = a\, e^{-bq_t}$	k=76.512 $mg.g^{-1}$	-	0.9581
4	Weber Morris/ Intraparticle diffusion	$q_t = k_i t^{1/2}$	k_i= 133.31 $mg.g^{-1}$	76.512 $g.mg^{-1}.h^{-1}$	**0.9920**

4. CONCLUSION

Study of Lead Metal Adsorption Isotherm and Kinetics Using a Adsorbent Combination of Chitosan and Coffee Ground Activated Carbon showed that the adsorption isotherm follows the Langmuir isotherm model with a correlation coefficient of 0.9970 with a maximum adsorption capacity of 1.0511 $mg.g^{-1}$ which indicates that chemical adsorption occurs in the mono layer with a homogeneous distribution of adsorption sites with constant adsorption energy and negligible interactions between lead metal molecules (adsorbate). Study of lead adsorption kinetics using chitosan-activated carbon coffee grounds following the Weber-Morris/intra-particle diffusion model with a correlation coefficient of 0.9920 with a diffusion rate of 76.512 $g.mg^{-1}.h^{-1}$ indicating that intra-particle diffusion is the rate step limiting in the overall biosorption process. Negative ΔG^o values indicate that the adsorption reaction takes place spontaneously, ΔH^o of 0.8130 indicates an endothermic reaction, and ΔS^o of 4.1888 indicates an increase in the randomness of the adsorption process at the adsorbent interface and lead during adsorption.

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The Processing of LDPE Plastic Waste into Renewable Fuel Using Waste Motor Oil

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ABSTRACT

The increase in population causes an increasing amount of solid waste, especially plastic waste. Plastic waste that cannot be decomposed in nature increases its number and causes environmental pollution. This research aimed to process plastic waste into alternative fuel oil using waste motor oil. The research methods consisted of designing a plastic waste processing device using waste motor oil as fuel and testing the device with a plastic burning process using a processing machine. The plastic waste processing device was produced as a stove to heat plastic waste fueled by waste motor oil using an electric blower to generate pressure into the reactor. The heating process produces steam flowing and processing in a distillation tube to produce oil. LDPE plastic waste could produce renewable fuel at the temperature of 140°C, but there were still burning residues. The distillation produced two types of fuel oil, yellow and black.

1. INTRODUCTION

The Hygiene and City Parks Service of Bengkulu City stated that the amount of transported waste each day is 600 m^3, with detail of 700 m^3/day in total, in which 600 m^3 is transported to Temporary Landfill (henceforth TPS – Tempat Pembuangan Sementara), and the rest is piled up, burned, or heaped in Final Processing Landfill (henceforth TPA – Tempat Pembuangan Akhir). Some waste is disposed of by the community in illegal TPS (Wijaya, Alfansi, & Benardin, 2013). The population growth in Bengkulu Province impacts increasing the amount of solid waste. Bengkulu City has an area of 14,482 Ha with a population of 360,772 people producing 1,082.32 m^3 of waste daily (Ronal, 2015).

The composition of the waste produced by human activities is organic waste (60-70%) and non-organic waste (30-40%). Furthermore, the second most significant component of non-organic waste is plastic waste, with a 14% percentage (Purwaningrum, 2016). The majority of plastic waste is the plastic bag and plastic packaging.

The use of plastic products that are not environmentally friendly causes various severe environmental problems (Krisyanti & Priliantini, 2020). Plastic is a versatile product, light, flexible, moisture resistant, strong, and relatively inexpensive (Fatimura, Sepriyanti, & Yunita, 2019). The characteristic of plastic is considered to provide convenience in daily human activity. Although it is considered practical and economical, plastic can cause plastic waste, which is very dangerous for the environment and its components (Utami & Ningrum, 2020). The danger is that plastic waste is a challenging waste to manage.

Plastic is a macromolecule formed by a polymerization process: assembling several simple molecules (monomers) through a chemical process into large molecules called polymers (Surono & Ismanto, 2016).

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Plastic is a polymer compound whose main constituent elements are Carbon and Hydrogen (Bow, Zulkarnain, Sihombing, Kharissa, & Salam, 2018; Surono & Ismanto, 2016). One of the raw materials often used is naphtha, a material produced from refining petroleum or natural gas (Surono & Ismanto, 2016). Furthermore, producing 1 kg of plastic requires 1.75 kg of petroleum to meet the needs of raw materials and the energy of the process (Ramanda & Dewiyani, 2022).

Indonesia is in second place in the world for dumping plastic waste into the sea at a rate of 0.52 kg of waste/person/day or equivalent to 3.22 MMT/year (Jambeck, Geyer, & Law, 2015). Plastic waste is a type of waste that cannot be decomposed, so if the waste is not managed correctly, it will cause environmental pollution.

Plastic waste is a source of problems because it cannot absorb water, decompose, or be degraded in the soil (Yana & Badaruddin, 2017). Plastic waste is an inorganic waste that is difficult to decompose in the soil. Plastic waste takes 50-80 million years to decompose. However, plastic waste has economic value as an energy source because plastic comes from petroleum (Bow et al., 2018; Kumar, Panda, & Singh, 2011). With a proper process, plastic waste can be produced into hydrocarbons as a primary energy source (Aditama, 2018).

Waste processing is an effort to reduce the volume of waste or change its form to become more valuable products by burning, composting, destroying, drying, and recycling the waste (Anonim, 2002). Recycling plastic waste can be conducted in various ways, such as turning plastic waste into attractive accessories and handicrafts. Moreover, with the advancement of science, plastic waste can be converted into fuel oil (henceforth BBM – Bahan Bakar Minyak) (Oktora, Alwie, & Utari, 2019; Wajdi, Sapiruddin, Novianti, & Zahara, 2020). The recycling process is conducted by converting the plastic waste into fuel, considering that the raw plastic material comes from petroleum derivatives. Then the plastic waste can be returned to hydrocarbon form as a primary energy source.

This research problem is that the processing of plastic waste into renewable fuel using waste motor oil in Bengkulu City still needs to be created. For this reason, a plastic waste processing machine with waste motor oil in the combustion process is needed.

The plastic used as research material was Low-Density Polyethylene (LDPE), which can be processed through heating. This type of plastic is made from petroleum and has been produced since 1933. This type of plastic is relatively thin, flexible, clear, and light. In daily life, this plastic is widely used by traders to pack their wares, and in households, it is used as garbage bags, shopping bags, plastic wrap/packaging, and multi-purpose plastics such as ziplock.

This LDPE plastic has long durability and can be used repeatedly, so the plastic obtained from the market can still be used for other purposes. Ideally, this type of plastic is only used once and recycled because it takes hundreds of years to decompose. Plastic waste in Bengkulu City has increased by 10% since 2022. The estimation from the Bengkulu City Environmental Service based on the current population, the amount of waste reaches 765 cubic meters. In contrast, the handled amount is approximately 485 cubic that goes to the final processing landfill (TPA).

Currently, many plastic waste processing devices can convert plastic waste into various products, for instance, crude oil, gasoline, diesel, premium, and kerosene, with some processes (Oktora et al., 2019). However, the processing still uses a heating system using fossil fuels, so the impression of saving energy still needs to be achieved (Abdullah, Irawati, Qomariah, & Ain, 2020).

The increase in the fossil fuel price and the scarcity of certain types of fuel have resulted in long queues of vehicles at various public gas stations (henceforth SPBU – Stasiun Pengisian Bahan Bakar Umum). The price adjustment was based on the Decree of the Minister of Energy and Mineral Resources Number 62 K/12/MEM/2020 on the Basic Price Formula in Calculation of the Retail Selling Price for General Oil Fuel Types of Gasoline and Diesel Oil Channeled through Public Gas Stations. Based on this condition, it is necessary to innovate the fuel oil processing from plastic waste with environmentally friendly technology.

The process of processing waste into fuel includes several processes, such as: (1) pyrolysis is the chemical decomposition of organic matter through a heating process without or little oxygen or other chemical reagents in which the raw material will undergo a breakdown of the chemical structure into a gas phase (Riandis, Setyawati, & Sanjaya, 2021). The pyrolysis process will break down long hydrocarbon chains from plastic polymers into short hydrocarbon chains. Then these molecules are cooled into a liquid phase (Nasrun, Kurniawan, & Sari, 2015; Ridhuan, Irawan, & Inthifawzi, 2019). Pyrolysis, a thermochemical process that occurs in an oxygen-free environment (Fombu & Ochonogor, 2021), has been used for charcoal production for many years (thousands of years).

Pyrolysis is used to convert waste products into biofuel, producing little or no waste after the process is carried out (Fombu & Ochonogor, 2021; Jahirul, Rasul, Chowdhury, & Ashwath, 2012), thereby causing the method to get more attention nowadays compared to other thermo-chemical conversion processes. The insulating chamber was designed to have a length of 20.3 cm, a width of 20.3 cm, and a height of 34.0 cm (Fombu & Ochonogor, 2021). This chamber was located between the heating chamber and the reactor's external body (having a height of 50.0 cm and diameter of 31.8 cm); (2) Distillation is the separation of a mixture in a solution based on boiling point differences (Nasrun et al., 2015).

The construction of plastic waste processing machines uses the principle of pyrolysis and multilevel distillation, in which the plastic will be processed in a reactor heated with methane gas (Prasetya, Rudhiyanto, & Fitriyanto, 2017). Pyrolysis, a thermochemical process that occurs in an oxygen-free environment, has been used for charcoal production for many years (thousands of years). The result of a previous study was a waste processing machine with a specification of 1 m long, 0.35 m wide, 1.35 m high, 30 kg weight, and 0.5 litres/30 minutes production capacity. Mass production of the machine can reduce the amount of plastic waste, but decreasing methane gas worldwide creates new problems (Prasetya et al., 2017).

Fuel oil (BBM) from plastic waste is produced by distillation. The pyrolysis process is carried out to melt and evaporate plastic waste in the reactor. First, the raw materials or plastic waste are cleaned and chopped. Then, the material is placed into the reactor through the input hole. In addition, the reactor is heated using a furnace fueled by liquefied petroleum gas (LPG) (Sumartono, Ibrahim, & Sarjianto, 2018).

This research aimed to make a plastic waste processing machine to process the plastic waste into renewable fuel oil using used waste motor oil. The motor oil used for engine maintenance will produce waste motor oil. In line with the development of cities and regions, the volume of waste motor oil continues to increase along with the number of motorized vehicles and machines (Azharuddin, Sani, & Ariasya, 2020).

Using motorized vehicles has various effects on environmental damage; one of the effects is pollution due to the waste of motor oil. Toxic waste (B3 – Bahan Berbahaya Beracun) is substances, energy, or other components that, due to their characteristic, concentration, or amount, either directly or indirectly, can pollute or damage the environment or endanger the environment, health, and sustainability of the human life and other living objects (Anonim, 2014; Azharuddin et al., 2020).

The toxic waste contains substances that pollute the air, water, and soil (Candra, Sulastry, & Anwar, 2016). This pollution will harm the environment if it is not recycled. One litre of waste motor oil can damage millions of litres of water sources in the soil, causing the soil to lose its nutrients (Herdito, Risna, & Lutfi, 2021). The environmental pollution due to waste motor oil has been widely reported in the mass media. The waste motor oil has substances of combustion residues that are acidic, corrosive, deposits, and carcinogenic heavy metals. The waste of motor oil is extensive, so special treatment is needed (Rubiono & Yasi, 2017).

Heretofore, the community's use of waste motor oil still needs to be improved, especially as fuel. The utilization of waste motor oil has yet to be maximized due to the absence of a suitable and perfect device to utilize waste motor oil as fuel for the community (Hidayat & Basyirun, 2020). The waste motor oil can be used as fuel for stoves in plastic waste-burning (Pratama, Basyirun, Atmojo, Ramadhan, & Hidayat, 2020).

Like diesel or gasoline, waste motor oil cannot achieve complete combustion. It happens because waste motor oil is not flammable, so there is no fogging like fuel in general. Used engine oil, however, has a relatively high calorific value, so it is interesting to be used this waste as a renewable fuel for heat generation. Therefore, the present experimental study has been conducted on used engine oil combustion in a vertical tube burner (Lekpradit & Namkhat, 2017).

2. METHODS

The utilization of waste motor oil in the process of processing plastic waste into alternative fuel oil (BBM) is carried out according to the block diagram in Figure 1 below.

This research is in the form of producing devices/machines for processing plastic waste using waste motor oil as fuel for the stove in the process of burning plastic waste. The conducted stages of this research are: 1) the plastic waste is put into the boiler for the burning process, which then produces steam; 2) the steam flows through a pipe that is immersed in a cooling tube, the result of cooling the steam will produce fuel oil; 3) The testing of the machine will produce renewable fuel oil that can be used as a substitute for fossil fuels. The analysis was carried out to determine how to change the form from gas to liquid fuel oil. The flow chart of this research can be seen in Figure 2 below.

3. RESULT AND DISCUSSION

This research was carried out in some stages, starting from the solid waste collecting in the form of plastic waste and liquid waste in the form of waste motor oil. The used plastic waste is crackle plastic collected from residential and tourist attraction areas, as shown in Figure 3 below.

Besides solid waste, liquid waste in the form of waste motor oil from local automotive workshops also burdens the environment. The waste motor oil was obtained from car workshops which collect the waste motor oil into drums. The waste motor oil contains harmful chemicals such as hydrocarbon and sulfur because of the motor oil's function to lubricate the metals in the engine. In addition, the waste motor oil contains residual fuel, copper, iron, aluminium, magnesium, and nickel that can cause environmental damage if not well treated before being dumped into the environment.

The waste motor oil in this study was used as fuel for the stove, which heat the plastic waste in the reactor. The stove furnace was designed as a cube with a pyramid top. The stove dimensions are 22 cm x 22 cm bottom area, 12 cm x 12 cm top area, and 30 cm total height.

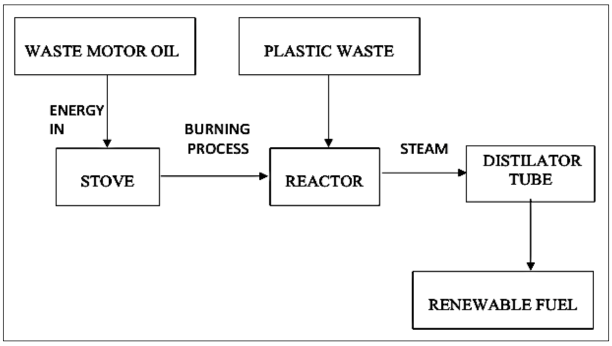

Figure 1. The Block Diagram of Processing Plastic Waste into Renewable Fuel

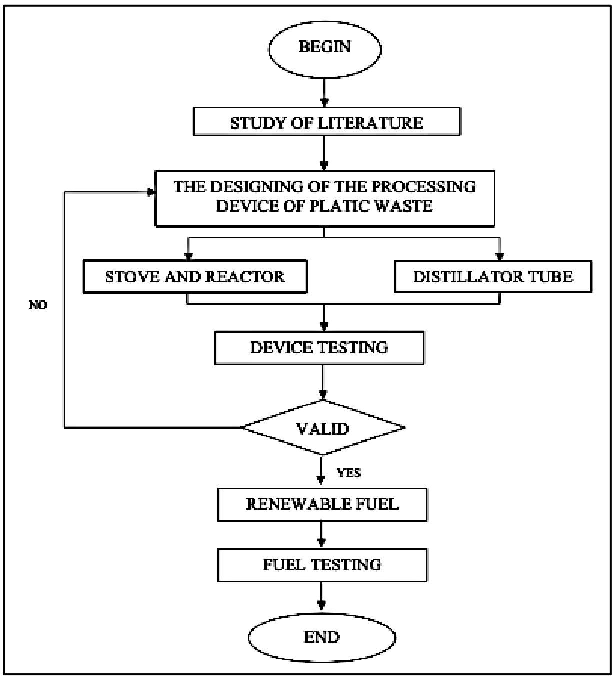

Figure 2. The Research's Flow Chart

Figure 3. The Plastic Waste

Figure 4. The Blower and Stove

Figure 5. The Reactor

Figure 6. The Distillation Tube

Figure 7. The Assembly and Performance Testing of the Device

The furnace was connected to a motor oil tube of 16 cm height for the burning process through a 100 cm long pipe. The tube held the motor oil continuously during the burning process through a pipe connected to an oil reservoir with a dimension of 30 cm x 30 cm and a height of 45 cm. The stove pressure in the heating process was given by an electric blower, as shown in Figure 4.

The next stage was to create a reactor, a furnace, and a distillation set to burn the plastic waste to produce oil. The furnace was designed as a reactor holder, which functions so that the fire generated from the stove can be maintained and the temperature entering the reactor can be constant. The furnace is 63 cm x 63 cm with a height of 44 cm.

The reactor is a device that can convert polypropylene (PP), polyethylene (PE), and polystyrene (PS) plastic waste into fuel oil. It is called the pyrolysis method: heating the plastic above 400°C without oxygen. The plastic will melt at this temperature and then turn into a gas. The gas flows into a distillation tube to cool and produce oil. In this study, the produced temperature in the burning process was only 140°C, so the plastic waste was not entirely decomposed and still produced residue.

Previous research on reactor design for refining tires into oil illustrates tire pyrolysis in a tubular stainless steel batch reactor of diameter D = 0.48 m and height H = 0.99 m. The overall size of the reactor was 2.49 m, and the shield length was 0.61 m (Aziz, Al-khulaidi, Rashid, & Islam, 2016). The process was carried out with maximum liquid production. The reactor wall was made from two 0.002 m stainless steel sheets, with a 0.04 m thick insulation layer (glass wool) between them. At the bottom of the reactor, a 0.20 m diameter tube was attached to remove char. Five spiral tubes of 0.019 m diameter (three U-shaped and two semi-hexagonal) were placed inside the chamber to improve fast heating. However, a fuel burner supplies the primary heat flux to the reactor. This furnace has a hole where the reactor was placed, two openings for supplying solid fuel, and four ports for removing ash.

Figure 8. The distillation process and fuel oil result

In this research, the reactor was designed according to the planned plastic waste (LDPE) capacity of 6 kg. The reactor has a size of 60 cm x 60 cm and a height of 60 cm. The dimensions of the reactor are made based on the capacity to be accommodated by 75 kg of plastic. A box was placed at the front of the reactor to collect the gas obtained from the burning process. The box was connected to the distillation set.

The box was given a connecting pipe from the plastic burning chamber to the gas chamber with a size of 20 cm x 60 cm and a height of 20 cm. In this section, an iron pipe was installed to connect the chamber to the distillation set. The reactor lid was designed to be practical so that it can be opened and closed but still airtight with a size of 40 cm x 33 cm and a height of 10 cm. One of the raw materials for making the reactor was a steel plate with a thickness of 3 mm, as shown in Figure 5.

The gas produced in the burning process flows into the distillation tube. The function of the distillation tube is to cool the gas so that the gas will condense and form a liquid. This liquid will become a renewable fuel. The distillation tube was made as a box with a size of 60 cm x 20 cm, a height of 20 cm, and a tilt position of 45°. The distillation tube was given a pipe that would be connected to the reactor. At the top of the distillation tube, an iron pipe with a stopper was attached. The length of the pipe is 55 cm which functions as a gas exhaust. At the bottom of the distillation tube are 2 (two) pipes on the left and bottom right sides. The pipe with a length of 45 cm was provided with a stopcock that would drain the produced renewable fuel in the cooling process. The height of the distillation tube foot is 83 cm with a width of 53 cm, as shown in Figure 6.

After the equipment was produced, the assembly and testing process was carried out to test the performance feasibility of the device before the actual experiment was conducted. The assembly and testing process of the device can be seen in Figure 7 below.

Following device assembly and testing, observations were conducted on the temperature generated from the stove that can be used to produce steam as needed. The optimum temperature obtained was measured using a thermometer, and the pressure was controlled due to the allowed maximum pressure so that the steam produced could produce oil.

The testing stage was conducted by heating the reactor, filled with plastic waste, and using a stove with waste motor oil fuel. The heat generated by the stove with a blower reached a temperature of 140ºC used to burn the plastic waste. The steam generated from the burning process was cooled through a pipe inserted into a distillation tube that converted the steam into a liquid. From the distillation tube, the resulting fuel oil came out through the faucet and was collected. The distillation results produced water and two types of fuel: yellow fuel and black fuel. The refining process and the fuel oil can be seen in Figure 8.

The produced fuel oil is similar to diesel fuel visually and characteristically in terms of colour and smell. The chemical composition of the produced fuel oil from the refining process will be tested in the laboratory for further research.

3. CONCLUSION

Based on the study's results, it can be concluded that the plastic waste processing machine using waste motor oil as fuel can operate and produce yellow and black alternative fuel oil. In plastic waste processing, the residue remains because the temperature reached in the heating process is only 140°C.

Further research is needed on the reactor material so that the generated temperature is more optimal than the current generated temperature and the heating results leave zero residues. The produced fuel needs to be tested in a laboratory to determine the composition and type of the fuel.

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Kementerian Perindustrian REPUBLIK INDONESIA

Global Context of Industry 5.0 : Current Trends and Challenges in Indonesia

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ABSTRACT

This article reviews the strategies and potential implications of implementing Industry 5.0 in Indonesia, emphasizing environmental impact, process technology, and energy conservation. To provide a comprehensive understanding of Indonesia's challenges and opportunities in transitioning to Industry 5.0 and to elucidate the impact of this shift on environmental sustainability, technological processes, and energy efficiency. An in-depth analysis was conducted on current technological trends, such as 3D printing, augmented reality, virtual reality, IoT, and AI, and their potential roles in the Indonesian industrial sector. We also explored the infrastructural needs, the significance of a skilled workforce, and the regulatory framework essential for a seamless transition. Findings highlight the critical importance of human-centric manufacturing, the potential benefits of Industry 5.0 technologies for environmental and energy efficiency, and the need for robust collaborations among government, industry, and research institutions for a successful transition. Recommendations emphasize infrastructure development, human resource enhancement, supportive policies, and multi-sectoral collaboration.

1. INTRODUCTION

The progression of the Industrial Revolution is evident through its various phases, transitioning from Industry 1.0's essential mechanization to the sophisticated digitization seen in Industry 4.0 (Destouet et al., 2023). Now, the global arena is advancing towards Industry 5.0. This phase underscores a blend of human and technological collaboration, aiming for a balanced coexistence between man and machine (Demir et al., 2019). To embody this vision, Industry 5.0 integrates advanced technologies including, but not limited to, 3D printing, Augmented Reality (AR), Virtual Reality (VR), the Internet of Things (IoT), and Artificial Intelligence (AI) (Mourtzis et al., 2022; Elshenawy et al., 2023).

With a commitment to enhancing production processes, Industry 5.0 champions a synergistic approach to manufacturing, placing humans at its core. Harnessing these groundbreaking technologies could profoundly augment environmental stewardship, refining process technology, and bolster energy conservation. Nonetheless, the journey to inculcate Industry 5.0 Indonesia's framework is complex – from infrastructural enhancements to upgrading workforce skills and sculpting favorable legislative environments (Hein-Pensel et al., 2023; Yin & Yu, 2022). Thus, a unified front between government bodies, industrial sectors, and academic circles becomes paramount to spur innovation and research.

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Globally, the buzz around Industry 5.0 has intensified. This paper endeavors to curate an overview of the prevailing trends and trajectories in Industry 5.0. By gauging its global momentum to spotlight potential challenges that might surface when introducing it to the Indonesian milieu. Recognizing that Indonesia's tryst with Industry 5.0 is still in its infancy, conjectures draw from an intricate understanding of its present global status. Through narrative to carve a roadmap for Indonesia, spotlighting strategic imperatives in areas like environmental preservation, advanced process technology, and energy efficiency during this pivotal industrial metamorphosis.

The essence of this article transcends a mere chronicle of the dynamic realms of Industry 5.0. In light of the seismic shifts the global industrial sectors are witnessing with the dawn of Industry 5.0, this manuscript not only stands as a contemporary dossier but also illuminates the distinctive barriers Indonesia, an emergent powerhouse, might face in its voyage to assimilate Industry 5.0. For Indonesian stakeholders, deciphering these intricacies is critical to charting a visionary yet pragmatic implementation path.

Delving deep, this review shines a light on the recent breakthroughs in Industry 5.0, its foundational technologies, and the intertwined challenges and prospects it ushers in for manufacturing. Highlighting environmental sustainability, avant-garde process technology, and energy thriftiness as pivotal axes (Demir et al., 2019; Destouet et al., 2023), the potential for Indonesia to refine these facets through Industry 5.0's lens is significant. This discourse aims to bequeath discerning insights, enabling Indonesia to navigate this transformative era and reap its advantages.

Navigating the transition from Industry 4.0 to 5.0, Indonesia is on the brink of a revolution. With aspirations to institute strategies accentuating environmental impact, advanced process technology, and energy prudence, lucidity and precision in elucidating these imperatives are non-negotiable. Marrying the nuances of Industry 5.0 with Indonesia's distinct challenges and potentials necessitates that our communication mirrors the rigor and meticulousness with which we approach this pivotal shift.

2. METHODS

This study employs a qualitative review approach. Undertook a systematic review of existing literature related to Industry 5.0, focusing on its implementation strategies and the challenges countries face, especially Indonesia. This method allows for a comprehensive understanding of the topic by synthesizing various perspectives and findings from multiple sources.

Instrument The research was conducted remotely, with sources primarily being academic journal publications focusing on Indonesia's industrial sector and transition to Industry 5.0. Academic databases were used to gather peer-reviewed articles, and platforms such as Google Scholar, Scopus, and ScienceDirect were utilized. Software VOSviewer was employed for qualitative data analysis, enabling us to categorize and code themes emerging from the literature.

Procedure The study began with a keyword search on the chosen databases, focusing on terms like "Industry 5.0", "Indonesia industrial challenges," and "sustainable industrial practices." After gathering a significant number of articles, a review was undertaken. Articles were classified as critical themes and selected using VOSviewer toward reading in depth. The data was then synthesized, and key findings related to Indonesia's transition to Industry 5.0 were identified.

3. RESULTS AND DISCUSSION

3.1. Diverse Perspectives on Industry 5.0: A Foundation For Indonesian Strategy

The rapid evolution of Industry 5.0 has led to many opinions and projections about its potential implications and best practices for implementation. Recognizing the importance of this diversity in thought, the manuscript gathers opinions from various experts in the field. Each perspective provides a unique insight into the challenges and opportunities of Industry 5.0, especially within Indonesia's unique industrial and socio-economic landscape. By synthesizing these varied viewpoints, we aim to offer a comprehensive strategy for Indonesia, ensuring the nation's approach is informed and innovative. Table 1 shows a comparative approach of the five industrial revolutions, highlighting the evolution in process technology, environmental impact, and energy conservation strategies.

3.2. The current stage of Indonesia in the transition to Industry 5.0

As a rapidly developing nation, Indonesia has shown significant strides in embracing industrial revolutions over the past decades. As of the recent assessment, Indonesia is predominantly in the Industry 4.0 phase, focusing on digitization, automation, and adopting the Internet of Things (IoT) in its manufacturing and industrial sectors. Several industries have started integrating intelligent technologies, data analytics, and AI-driven processes into their operations.

However, while Industry 4.0 principles are being adopted, the shift towards Industry 5.0 — emphasizing human-machine collaboration, customized production, and enhanced sustainability — is in its nascent stages. The government has launched initiatives and roadmaps to drive the country towards Industry 4.0 and 5.0. These include the "Making Indonesia 4.0" strategy, which lays the foundation for a more advanced stage of industrialization. However, the complete realization of Industry 5.0 is still a vision for the future, with several challenges to overcome and opportunities to seize.

Understanding Indonesia's current position in the industrial evolution spectrum is crucial as it provides context to the subsequent discussion on strategies for the transition to Industry 5.0.

As one of Southeast Asia's largest economies, Indonesia has been working diligently on embracing the next industrial revolution, colloquially referred to as Industry 5.0. This phase of the industrial revolution emphasizes collaboration between humans and machines, bridging the gap between technological advancements and human-centric approaches to ensure efficient and humane production processes.

3.3. Human collaboration in the packaged drinking water industry

One notable development in the Indonesian industrial landscape is the pilot projects in the Packaged Drinking Water (AMDK) sector. Historically, the production processes in this industry, particularly packaging, have been predominantly automated. However, the transition towards Industry 5.0 has seen a more significant involvement of human roles in production. The rationale is to leverage human workers' unique insights, dexterity, and adaptability while machines provide precision, speed, and consistency.

Table 1. Evolution of industrial revolutions: Differences in process technology, environmental impact, and energy conservation

Industrial Revolution	Process Technology	Environmental Impact	Energy Conservation
Industry 1.0	Mechanization using steam and water power	Significant increase in emissions	Reliance on non-renewable sources (coal, wood)
Industry 2.0	Mass production using electrical energy	Continued rise in pollution	Increase in electrical energy consumption
Industry 3.0	Automation using electronics and IT	Mixed; adoption of cleaner tech	Improved efficiency but increased consumption
Industry 4.0	Digitalization and the advent of intelligent systems	Focus on green technologies	Emphasis on renewable energy and energy-saving
Industry 5.0	Collaboration between humans and machines	Human-centric & sustainable	Enhanced conservation through AI and optimization

The goal of these pilot projects is to create a harmonious working environment where machines can support and augment the abilities of their human counterparts. This approach increases productivity, reduces errors, and leads to a more fulfilling and meaningful work experience for employees.

3.4. AI-Based production control in the ozonation process

Another noteworthy implementation is in the process of ozonation, a crucial step in purifying water for consumption. With the challenges posed by variations in source water quality and the imperative to ensure consistent, safe drinking water, companies have turned to AI-powered databases. These databases collate extensive data on water sources, ozonation parameters, and final product quality.

With the help of AI, predictions can be made about the future quality of the product. It allows industries to make proactive decisions, optimize the real-time ozonation process, and consistently produce high-quality drinking water. Integrating AI ensures the product meets stringent safety standards while optimizing resource use and minimizing waste.

Apart from the sectors above, various industries in Indonesia have been adopting similar approaches. From intelligent manufacturing that employs sensors and IoT devices to monitor and optimize factory operations to the agriculture sector leveraging drone technology and AI for precision farming — the wave of Industry 5.0 is being felt throughout.

It is worth noting that the government, aware of the potential of Industry 5.0, has been implementing policies and initiatives to foster an environment conducive to this transition. It includes investments in infrastructure, upskilling programs for the workforce, and collaborations with international tech giants.

The journey of Indonesia toward Industry 5.0 is a testament to its commitment to embracing the future while being cognizant of the human element in the industrial process. By harmonizing technology with human collaboration and utilizing the potential of AI, Indonesia is poised to become a leader in the next phase of the industrial revolution.

3.5. Industry 5.0 Environmental Technology

Industry 5.0 emphasizes human centricity, sustainability, and resilience throughout the manufacturing process, which includes air pollution control technologies, wastewater treatment, and solid waste and hazardous waste management (Destouet et al., 2023). Effective and sustainable environmental technologies are critical in Industry 5.0 to address diverse industrial sectors' environmental challenges.

Blockchain technology has been considered an air pollution control method in Industry 5.0 to resolve centralization, privacy, latency, and security concerns in industrial IoT infrastructure (Elshenawy et al., 2023). The proposed solution, FusionFedBlock, combines Blockchain with Federated Learning to maintain anonymity between industrial divisions. Efficient and sustainable environmental technologies will play a vital role in reducing the negative environmental impact of industrial operations in the context of Industry 5.0. The Indonesian industry can meet its sustainability targets and minimize environmental impact by implementing air pollution control technologies, wastewater treatment, solid waste, and hazardous waste management (Destouet et al., 2023). Table 2 shows the impact of Industry 5.0 in Terms of environmental impact, efficiency, and energy conservation.

One of the primary objectives of implementing Industry 5.0 is to optimize manufacturing processes while minimizing environmental impact. For example, AI and data analytics technologies can contribute to this goal. Li et al. (2022) demonstrated implementing a NOMA-based cognitive radio network with a hybrid FD/HD relay, which allows opportunistic switching of RATs and offloading methods to reduce delays, thereby enhancing the efficiency and reliability of communication systems in Industry 5.0.

Furthermore, AI technology can improve resource allocation systems, increasing production efficiency (Ahmed et al., 2022). Ahmed et al. (2022) proposed a Secondary Resource Allocation (SRA) method based on multiple time scales in conjunction with the QMix Multi-Agent Reinforcement Learning (MARL) algorithm, which can increase the overall utility value by 70% and job completion rate by 6%, enhancing the efficiency of industrial operations.

Industry 5.0 has led to significant changes in design engineering, mainly through AR, VR, IoT, and AI technologies (Mourtzis et al., 2022). An example of this technology application is the development of automated tool exchange systems for robots, which can improve efficiency and accuracy in equipment replacement. Moreover, Industry 5.0 emphasizes creating more efficient technology for detecting and controlling pollution.

Table 2. Impact of Industry 5.0 in Terms of environmental impact, efficiency, and energy conservation

Aspect	Positive Impact	Negative Impact
Environment	• Reduction of greenhouse gas emissions. • Use of renewable energy sources. Waste reduction through process efficiency	• Disposal of e-waste. • Unsustainable use of natural resources.
Process Technology	• Process automation that improves efficiency. • Improved product quality control. • Increased flexibility in the production process	• Job loss due to automation. • High technological dependability.
Energy Conservation	• Use of energy-friendly technologies. • Better energy management thanks to IoT. • Reduction of energy consumption through process optimization.	• Increased energy consumption in certain sectors.

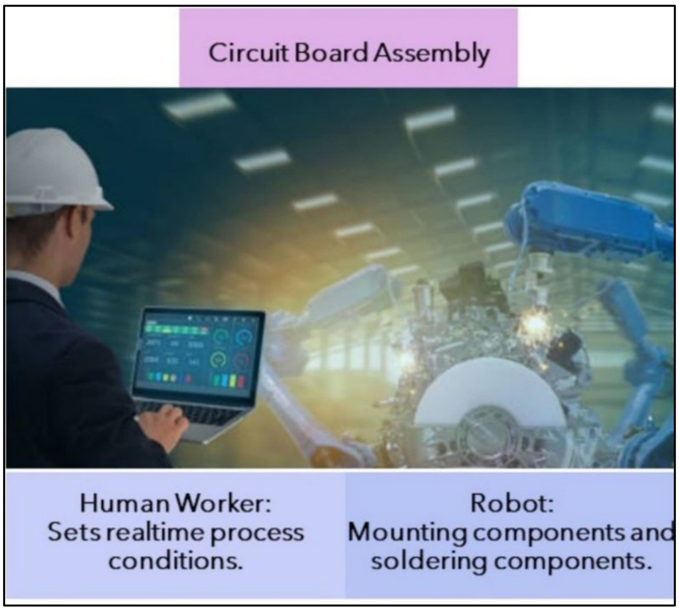

Figure 1. Illustration of the concept of cooperation between humans and robots in the context of Industry 5.0

AI technology in Industry 5.0 also enhances supply chain resilience and sustainability (Ahmed et al., 2022). Challenges in Industry 5.0 involve human collaboration in a human-centered manufacturing environment. Wang et al. (2023) suggested a Digital Twin-based strategy to address safety management challenges in such a manufacturing context. This approach includes machine-readable semantic reasoning frameworks, insecure state ontologies, high-speed virtual Digital Twin workshops, virtual dataset generation, network target identification, and tests to demonstrate the proposed method's effectiveness.

Figure 1 illustrates the cooperation between humans and robots in Industry 5.0, showing how technologies such as cobots (collaborative robots) and augmented reality enable more efficient and safe interactions between human workers and machines. Robots assist human workers in assembling small components on circuit boards with exact spot welding. Robots can provide speed, precision, and consistency that are difficult for human workers to achieve.

Orea-Giner et al. (2022) investigated the impact of deploying robots in hotels on overall TripAdvisor rankings in the tourism setting. The study found a connection between emotions and attitudes elicited by hotel robot interactions, the robot's functional typology, traveler classifications, and hotel evaluations. This finding illustrates how AR, VR, IoT, and AI technologies can be leveraged to enhance customer experience and service quality in various industries.

Industry 5.0 offers opportunities for developing and utilizing environmentally friendly materials as alternatives in the industrial sector. Mourtzis et al. (2022) explored the potential of 3D printing in creating automated tool interchange systems for robotic arms in Industry 5.0. This study developed an efficient system that allowed for adequate tool replacement and demonstrated the possibility of creating collaborative systems for educational instruction using robots.

Furthermore, Mirza et al. (2023) showed how reinforced deep learning (DRL) could be used to increase accuracy, reliability, and real-time decision-making capabilities in optimizing task procrastination offloading in Industry 5.0-based vehicle edge computing networks (VECNs). These findings illustrate how technological advancements in Industry 5.0 can support developing and using environmentally friendly materials by enabling more efficient and sustainable operations (Mirza et al., 2023).

Overall, Industry 5.0 presents opportunities for developing and using eco-friendly materials as industrial alternatives through various innovative technologies, such as 3D printing and AI-based techniques like DRL. Adopting these environmentally friendly products will help reduce the industry's negative environmental impacts and promote sustainability in the manufacturing process.

Energy conservation is a critical aspect of Industry 5.0, and technologies like IoT and AI can help optimize energy consumption. Mirza et al. (2023) demonstrated how AI technologies, such as deep reinforcement learning (DRL), can be used to increase accuracy, reliability, and real-time decision-making capabilities in minimizing offloading job delay in Industry 5.0-based vehicle edge computing networks (VECNs). This study highlights the potential of IoT and AI technologies for reducing energy costs and consumption through process optimization.

Renewable energy and efficient energy conversion technologies are also essential in Industry 5.0. Harihastuti et al. (2021) described a full-scale implementation of a high-performance anaerobic reactor with substrate modification and effluent recirculation for vintage sugarcane degradation and biogas generation. In the context of Industry 5.0, this technology has the potential to produce renewable energy and enhance energy conversion efficiency.

IoT and AI technologies, renewable energy, and efficient energy conversion technologies can be harnessed to optimize energy use and support environmental sustainability in Industry 5.0. By integrating technologies such as DRLs, membrane-less MFCs, and high-performance anaerobic reactors, Industry 5.0 can reduce energy consumption and generate renewable energy, thus promoting energy conservation in the industrial sector.

3.6. Global Industry 5.0 Innovation

Industry 5.0 emphasizes numerous innovations and discoveries in areas such as air pollution control, wastewater treatment, solid waste B3 management, and energy conservation to support its process technology. AI technologies, such as real-time tracking via IoT, can be employed in Industry 5.0 to build robust and sustainable supply chains (Ahmed et al., 2022). Furthermore, Yin and Yu (2022) recommend adopting and implementing a digital green knowledge framework for Industry 5.0, which can enhance the effectiveness of digital green innovation practices by emphasizing the need for collaboration with external knowledge seekers.

Human-robot Collaboration is a significant aspect of Industry 5.0. Pozo et al. (2022) discuss the open-lab approach to building collaborative robotic environments in educational teaching. Rannertshauser et al. (2022) propose the concept of human-centricity in the design of production planning and control systems to eliminate errors caused by cognitive biases. Moreover, Wang et al. (2023) suggest a Digital Twin-based safety management strategy for addressing safety management challenges in human-centered production aligned with Industry 5.0 requirements.

In the context of Industry 5.0, technologies such as Blockchain and Federated Learning have emerged. Elshenawy et al. (2023) propose a solution that combines Blockchain with Federated Learning to ensure anonymity among industry divisions while storing and validating global models.

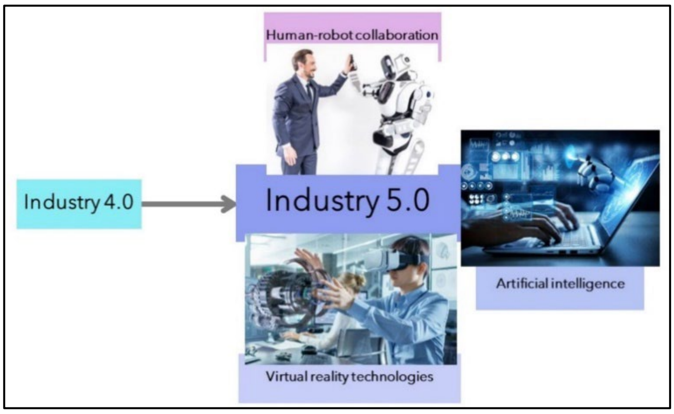

Figure 2. Industry 5.0 flowchart

Industry 5.0 has brought about significant innovations and improvements in various industrial sectors. Multi-Agent Reinforcement Learning (MARL) technology in resource allocation is a critical component of Industry 5.0 (Ahmed et al., 2022). According to Ahmed et al. (2022), this technology increases total utility value by up to 70% and results in a 6% rise in job completion rates, contributing to developing more effective resource allocation systems for connected and autonomous vehicles (CAV).

Robots in the hospitality industry have significantly impacted TripAdvisor's overall rankings, highlighting the connection between emotions and sentiments generated by robot interactions and hotel evaluations (Orea-Giner et al., 2022). Industry 5.0 also encompasses a green digital knowledge adoption-implementation framework, which can help manufacturing organizations enhance the performance of their green digital innovations (Yin & Yu, 2022). Pozo et al. (2022) provide an example of Industry 5.0 technology through an open laboratory approach to collaborative robotic environments in educational instruction. Figure 2 shows the Industry 5.0 flowchart illustrating the transition from Industry 4.0 to Industry 5.0, including vital technological changes, such as increased human collaboration, artificial intelligence, and virtual reality technologies.

Wang et al. (2023) suggest a Digital Twin-based solution for addressing safety management challenges in human-centered manufacturing within the context of environmental and security management. This strategy includes machine-readable semantic reasoning frameworks, hazardous state ontologies, and high-reliability virtual Digital Twin workshops. Thakur and Kumar Sehgal (2021) propose a heterogeneous architecture for Smart Cyber-Physical Systems (SCPS) in the context of renewable energy that can be applied in various industries such as petroleum, fertilizer, paper, cement, space exploration, and automobile production.

Under Industry 5.0, Mourtzis et al. (2022) developed an automated tool exchange system for 3D printing design. However, Hein-Pensel et al. (2023) emphasize the importance of maturity assessment in Industry 5.0 adoption, particularly for small and medium-sized businesses with limited resources. This study highlights the need for a more human-centered approach to manufacturing, focusing on sustainability and resilience (Destouet et al., 2023).

To implement Industry 5.0 in Indonesia, concentrating on long-term, flexible, and innovative strategies is crucial. Human centricity, sustainability, and resilience in manufacturing will be critical to successfully transitioning to Industry 5.0 (Destouet et al., 2023). Moreover, efforts to address challenges in workforce skill development and new technology adoption will be essential in implementing Industry 5.0 in Indonesia.

3.7. Global Industry 5.0 Challenges

Industry 5.0 presents several significant challenges that Indonesia must address to adopt and implement this new technology successfully. One primary concern is human-centric manufacturing, which requires a deep understanding of the complex interconnections between humans, machines, and the environment (Wang et al., 2023). Furthermore, Lu et al. (2022) note that there is no common understanding of the nature of human-centered manufacturing, emphasizing the importance of addressing this issue in Industry 5.0.

Another challenge lies in the lack of research on organizational issues arising from human-robot Collaboration (Demir et al., 2019). Implementing technologies such as 3D printing, AR, VR, IoT, and AI in collaborative systems for educational instruction presents obstacles (Mourtzis et al., 2022). Moreover, utilizing Blockchain technology and Federated Learning in the context of Industry 5.0 raises concerns about centralization, privacy, latency, and security risks in industrial IoT infrastructure (Elshenawy et al., 2023).

Industry 5.0 builds upon Industry 4.0, emphasizing the role of humans and technology working together to achieve better outcomes (Coelho et al., 2023). A key aspect of Industry 5.0 is the integration of materials characterization, modeling, and data science to foster research and innovation in materials manufacturing (Charitidis et al., 2022). This interdisciplinary approach is essential for developing advanced materials and processes that cater to the needs of future industries. Table 3 compares Industry 4.0 and Industry 5.0 in various aspects.

In the Meetings, Incentives, Conferences, and Exhibitions (MICE) industry context, Hur et al. (2022) investigated the readiness of MICE 5.0 by examining technology use through big social media data. This approach highlights the importance of understanding user behavior and technology adoption to implement Industry 5.0 concepts successfully. Khan et al. (2023) proposed a strategic approach to overcome Industry 4.0 challenges by focusing on the changes and improvements brought by Industry 5.0, emphasizing the need for organizations to adapt and evolve by embracing opportunities offered by human-centric manufacturing (Lu et al., 2022).

Table 3. Comparison of Industry 4.0 and Industry 5.0

Aspects	Industry 4.0	Industry 5.0
Main focus	Automation and efficiency	Human-machine Collaboration and sustainability
Key technologies	IoT, big data, AI, robotics	IoT, big data, AI, collaborative robotics, augmented reality, and virtual reality
Environmental impact	Improved energy and material efficiency	Reducing carbon footprint, green energy use
Workforce impact	Job loss due to automation	The increased role of humans in the process
Impact on the production process	Efficient mass production	More flexible and adaptive production

Leng et al. (2022) provided insights into the prospects and retrospects of Industry 5.0, underlining the importance of understanding the historical context and future possibilities. Prassida and Asfari (2022) developed a conceptual model for accepting collaborative robots in Industry 5.0, addressing the need for a human-centered approach to technology adoption. Qahtan et al. (2022) explored integrated sustainable transportation modeling approaches for electronic passenger vehicles in Industry 5.0, emphasizing the importance of considering sustainability and environmental factors in developing and implementing new technologies.

Sachsenmeier (2016) discussed the relevance and implications of bionics and synthetic biology in Industry 5.0, highlighting the potential of these fields to revolutionize various industries by combining the best biological and technological systems. Wagner et al. (2023) presented IndustrialEdgeML, an end-to-end edge-based computer vision system for Industry 5.0, illustrating the role of advanced technologies like computer vision in supporting the transition towards Industry 5.0.

From a knowledge management perspective, Yin and Yu (2022) highlight challenges in integrating digital technology with green innovation. Concerns include promoting digital green knowledge development and managing digital risks and difficulties. Thakur and Kumar Sehgal (2021) argue that implementing their proposed architecture for intelligent heterogeneous systems may present challenges in various sectors.

Workforce skill development and new technology adoption are also significant concerns in Industry 5.0 (Destout et al., 2023). Hein-Pensel et al. (2023) assert that limited resources make it difficult for small and medium-sized enterprises (SMEs) to adopt successful digitalization plans. Ahmed et al. (2022) also emphasizes the potential for increased utility and job completion rates by applying their suggested approach but acknowledge that limited resources pose constraints.

Industry 5.0 represents a new era in which humans and technology work together synergistically to create innovative solutions across various domains. The successful implementation of Industry 5.0 concepts relies on a deep understanding of the interplay between materials, technology, data science, and human factors, as well as the adoption of sustainable practices and the integration of cutting-edge technologies like bionics, synthetic biology, and computer vision (Charitidis et al., 2022; Coelho et al., 2023; Hur et al., 2022; Khan et al., 2023; Leng et al., 2022; Lu et al., 2022; Prassida & Asfari, 2022; Qahtan et al., 2022; Sachsenmeier, 2016; Wagner et al., 2023).

Table 4. Implementation strategy in Indonesia

Government	Industry	Research Institutes
Policy and regulation	Technology Innovation	Research and development
Infrastructure Support	Adoption of New Technologies	Training and Education
Incentives and funding	Research and Development Investment	Partnership with Industry

Table 5. Strategy collaboration between government, industry, and research institutions

Strategy	Information
Infrastructure development	Improve connectivity, transportation, and access to renewable energy.
Human Resource Development	Train a skilled workforce in Industry 5.0 technology.
Policies and regulations	Implement policies that support the transition and protect workers.
Collaboration between stakeholders	Encourage cooperation between government, industry, and research institutions.

Addressing these challenges will be critical in implementing Industry 5.0 in Indonesia, emphasizing long-term, flexible, and innovative implementation strategies. Human centricity, sustainability, and resilience in manufacturing will be crucial for successfully transitioning to Industry 5.0.

3.8. Industry 5.0 Implementation Strategy In Indonesia

Indonesia's Industry 5.0 implementation strategy encompasses several crucial elements, including infrastructure development and cultivating a skilled workforce. It is essential to foster a comprehensive understanding of the intricate interconnections between humans, machines, and the environment in human-centric manufacturing and establish a common understanding of its core principles. Enhancing the capabilities of adaptable and skilled human resources is necessary to address these challenges. The difficulties small and medium-sized enterprises (SMEs) face in successfully executing digitization plans underscore the need for a supportive infrastructure.

AI-enhanced process and simulation technologies, in conjunction with data analytics within the context of Industry 5.0, can aid the Indonesian industry in achieving more efficient and environmentally friendly production. Adopting these technologies will support implementing the Industry 5.0 strategy, emphasizing energy reduction and effective waste management. Table 2 illustrates the impact of Industry 5.0 in terms of environmental impact, efficiency, and energy conservation.

For a smooth transition to Industry 5.0, governments must establish regulations and policies that protect affected workers while fostering an environment conducive to innovation. Additionally, addressing the challenges of merging digital technology with green innovation requires significant policy support in knowledge and risk management.

Collaboration among government, industry, and research institutions is essential for promoting innovation and research in Industry 5.0. The scarcity of research on organizational challenges stemming from human collaboration highlights the importance of cooperation among various stakeholders. Furthermore, technologies such as 3D printing, augmented reality, virtual reality, IoT, and AI play a crucial role in developing collaborative educational systems involving robots and addressing centralization, privacy, latency, and security concerns in industrial IoT infrastructure.

Table 4 depicts the implementation strategy of Industry 5.0 in Indonesia. Table 5 outlines the strategy focusing on improving infrastructure, developing a skilled workforce, implementing supportive policies and regulations, and collaboration among stakeholders. By addressing these areas, the industry can successfully transition to Industry 5.0 and thrive in the new era of advanced manufacturing.

In conclusion, implementing Industry 5.0 in Indonesia necessitates a strategy encompassing infrastructure development, skilled workforce enhancement, supportive laws and regulations, and coordination among government, industry, and research institutions. This approach will enable a long-term, adaptable, and innovative transition to Industry 5.0, emphasizing human-centricity, sustainability, and resilience in manufacturing.

4. CONCLUSION

This article examined the strategies and implications of adopting Industry 5.0 in Indonesia, focusing on environmental impact, process technology, and energy conservation. The key findings highlight the importance of embracing Industry 5.0 in Indonesia to promote sustainability, efficiency, and innovation within the industrial sector, aligning with global trends.

Technologies such as 3D printing, AR, VR, IoT, and AI play a crucial role in establishing collaborative systems for educational instruction using robots and addressing centralization, privacy, latency, and security concerns in industrial IoT infrastructure as part of Industry 5.0. A deep understanding of the complex interactions between humans, machines, and the environment is essential for human-centric manufacturing.

Furthermore, infrastructure development and cultivating a skilled workforce are necessary to facilitate Industry 5.0 implementation. Policies and regulations that promote knowledge management and risk management will protect vulnerable workers while fostering an environment conducive to innovation. Collaboration among government, industry, and research institutions is critical for driving innovation and research in Industry 5.0.

In conclusion, the implementation of Industry 5.0 in Indonesia has the potential to significantly improve environmental impact, process technology, and energy conservation. By focusing on infrastructure development, skilled workforce enhancement, supportive laws, and collaboration between government, industry, and research institutions, Indonesia can achieve a sustainable, adaptable, and innovative transition to Industry 5.0.

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Synthesis of Silica Nanoparticle Made from Lampung Pumice Modified with Sonication Parameters for Size and Purity

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ABSTRACT

Silica nanoparticles are widely utilized nanomaterials in various industries due to their unique characteristics. Homogeneous nanoscale size is preferred to obtain superior properties. This research was conducted to determine the sonication parameters of pumice rock synthesis on silica size and purity formation. Silica synthesis was carried out until a white gel formed, followed by sonication at temperatures of 30°C, 60°C, and 80°C for 1, 2, and 3 hours. The purity of silica was analyzed through X-ray fluorescence results, X-ray diffraction, and SEM imaging for morphology analysis. The synthesis results followed by the sonication process had the highest SiO_2 concentration of 98.97%. The sonication temperature had a significant effect and contributed 67.25%, higher than the sonication time of 22.4%. The highest SiO_2 concentration of >98% was achieved at 40°C for 1.5 hrs. Meanwhile, for particle size, both parameters have a significant effect with an error value of α: 3.14%. Particle size <6 nm was obtained with a sonication temperature of 50°C for 2 hours. The sonication process can increase the concentration and reduce the size of the synthesized silica particles by selecting appropriate independent variables.

1. INTRODUCTION

Indonesia possesses a wealth of both metallic and non-metallic mineral resources. Among the non-metallic resources is pumice, a light-colored stone type originating from volcanic eruptions forming distinctive zone atop silicate lava (Kumalawati and Mastaram, 2013). Indonesia ranks among the countries with the most active volcano in the world, with around 129, and comprising about 30% of the world's active volcano (Pratomo, 2006).

Among these active volcano is Mount Krakatau, located in Lampung Province, which erupted in 1883. This eruption has endowed Lampung Province with numerous reserves of pumice originating from volcanic sediment. most of which are SiO_2 (77.79%) and Al_2O_3 (12.72%). These eruption materials were spread to several areas in Lampung Province, one of which can be found around the beach of Gubug Garam, south of Tarahan City, Lampung.

Ersoy et al (2010) reported that pumice contains oxides of SiO_2, Al_2O_3, MgO, Na_2O, CaO, Fe_2O_3, K_2O, and others. The most dominant oxide contained in pumice is SiO_2 of 70.21%. Silica also known as SiO_2 is a mineral composed of two elements: silicon (Si) and oxygen (O_2). Nano silica, on the other hand, is an amorphous material composed of Si-O-Si bond with a silanol group (Si-OH) and is nano-sized.

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The availability of silica is abundant in nature, and so widely used in industrial fields such as raw materials for glass, ceramics, cement, and other industries. Silica can be obtained from quartz sand, granite, and pumice, while plant-derived silica is sourced from bagasse, corn cobs, and rice husks.

Silica dissolves in alkaline conditions and settles in acidic conditions. Therefore, silica extraction from pumice with NaOH was carried out to obtain silica. The highest silica content, 96.3%, was achieved with 3.0M NaOH variation, representing 18.5% increase from the original pumice silica content. Silica settles at pH 7; thus, to achieve this pH condition, the extracted filtrate dripped with H_2SO_4 solution to fasilitate silica settling. Subsequently, the resulting precipitate yields silica gel.

The silica obtained from the extraction still contains impurities such as Fe_2O_3 and Al_2O_3. The Silica purification process is carried out to remove these impurities by washing the silica using an acid solvent (HCl), which is effective in reducing the metal impurity content of 70.22%.

Nanomaterial is a material ranging in size from 1 to 100 nm. Material in nano size has an advantage over the same material in a larger size, nano-sized material has particles with a high interaction surface area. The more particles that interact, the stronger the bond between the particles, so the material is easier to react. One way to make nano-sized material is by sonication.

The sonication method is one method that can be applied to make smaller and homogeneous particle sizes. The key parameter for the utilization of sonication are temperature and time. The sonication method is widely used due to its effectiveness in producing nano-sized samples and separating the agglomeration of particles.

This research aims to determine the effect of variations in temperature and sonication time on pumice-based silica. The research is expected to provide valuable insights into the application of pumice as nano silica, particularly using sonication, in the industrial sector in Indonesia, such as the glass and cement industry, where silica is commonly utilized.

2. METHODS

Pumice stone from Lampung Province was washed with distilled water and dried at 80-110°C for 24 hours. Subsequently, the dried pumice stone was crushed with a mortar and meshed with ASTM: E11 through a 200 mesh sieve to obtain a fine material. It was then washed again using distilled water and calcined at 800°C for 4 hours.

The synthesis of silica begins by mixing 2.5 grams of pumice powder with 150 mL NaOH, followed by refluxing for 24 hours using a magnetic stirrer at 100°C. The extraction result is then filtered, and the filtrate was collected. The filtrate was then dripped with 50 mL H_2SO_4 until pH 7 to get a gel. The gel was dried in an oven for 24 hours at 80-100°C and then crushed to obtain silica powder. Next, the silica was mixed with 150 mL HCl and refluxed for 4 hours at 110°C. The resulting reflux materials were filtered, washed with distilled water and the residue was taken. Finally, the residue was dried for 24 hours at 110°C.

The sonication process started by mixing 100 mL of distilled water and 1 gram of silica powder. The mixture then inserted into the ultrasonic tube for sonication. Variation of temperature and sonication time are determined based on Design of Experiment (DOE) using Minitab 19 software, as shown in Table 1. The silica residue from sonication process was dried for 24 hours at 80°C-110°C and then calcined at 800°C for 4 hours to produce pure white silica. The chemical content of raw materials and results were analyzed using PANalytical's MiniPal 4 energy-dispersive XRF Bench-Top, crystal structure using X-ray diffraction type 3 E'xpert Powder, and morphology using FESEM Thermo Scientific Quattro S.

Table 1. Design of Experiment (DOE) for Sonication Process

No Samples	Temperature (°C)	Time (hrs)
1	80	3
2	80	2
3	60	1
4	30	1
5	80	1
6	60	2
7	30	3
8	30	2
9	60	3

3. RESULT AND DISCUSSION

3.1. X-R Fluorescence Characterization Results of Pumice

The results of the X-RF characterization of pumice are shown in Table 2. This chemical content resulted from the raw material before the synthesis and sonication process.

The results of raw material concentration are in accordance with previous research, indicating that the content of pumice has the most dominant silica compound. This shows that pumice is one of the abundant and easily accessible sources of silica.

The results X-RF characterization of silica after the synthesis are shown in Table 3. After the synthesis of pumice, the silica content reached 98.80 wt%, indicating a 28.99 wt% increase. The pumice synthesis process has reduced the impurities in the formed silica. The highest impurities were P_2O_5 at 0.72% and CaO at 0.37%.

3.2. Analysis of Variance (ANOVA) for Silica (SiO_2) Concentration

The results of the XRF silica test after the sonication process are shown in Table 4. below. The lowest SiO_2 content was formed in the specimen using a temperature of 80°C with a sonication time of 1 hour. Meanwhile, the highest SiO_2 content was obtained at a temperature of 60°C with a sonication time of 2 hours. The ANOVA for SiO_2 concentrations is shown in Table 5.

The highest contribution to the SiO_2 concentration is temperature, accounting for 67.25%. This parameter also has a significant effect, indicated by the P-value <5%, which is 0.018. Therefore, the null hypothesis (Ho) is rejected, concluding that temperature have significant effect on SiO_2 concentration. On the other hand, the time parameter contributes 22.4%, but it does not significantly affect the SiO_2 concentration. An error of 10.36% indicates that other independent variables have an effect.

The prediction of (SiO_2) concentration resulting from the correlation of independent variables shown in Fig. 1.

More than 98% SiO_2 concentration can be obtained by adjusting the temperature and time within the dark green area. Temperatures between 40 and 65 °C and times ranging from 1.5 to 3 hours yield the highest concentration. Notably, at low temperatures, maximum concentrations can also be obtained with a minimum time of 1.5 hrs. This contour plot facilitates the designer's choice of the DoE to produce the maximum SiO_2.

Table 2. X-RF Characterization Results of Pumice

Compound	Concentration (%)
SiO_2	69.81
Al_2O_3	9.24
Fe_2O_3	7.90
CaO	5.05
K_2O	4.96
TiO_2	1.22
P_2O_5	0.93
MnO	0.26
MgO	0.20
ZrO_2	0.10

Table 3. X-RF Characterization of Silica After Synthesis

Compound	Concentration (%)
SiO_2	98.80
Al_2O_3	0.04
CaO	0.37
TiO_2	0.01
P_2O_5	0.72

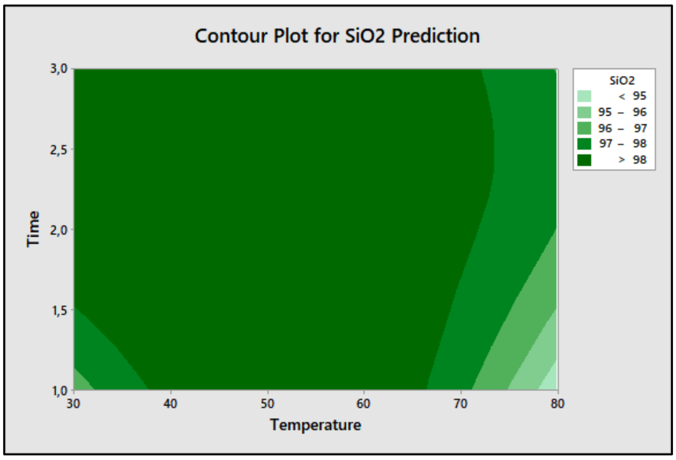


Figure 1. Independent Variables Correlation for SiO_2 Concentration

Table 4. Silica Concentration After Sonication Process

Temperature (°C)	Time (hrs)	SiO_2 (%)
80	3	96.95
80	2	96.99
60	1	98.81
30	1	96.52
80	1	94.24
60	2	98.90
30	3	98.86
30	2	98.82
60	3	98.97

Table 6. Silica Size After Sonication Process

Temperature (°C)	Time (hrs)	SiO_2 Size (nm)
80	3	12.602
80	2	15
60	1	13.536
30	1	16.712
80	1	17.827
60	2	6
30	3	11.383
30	2	14.970
60	3	5.303

Table 5. ANOVA for Transformed Response

Source	DF	Seq SS	Contribution (%)	Adj SS	Adj MS	F-Value	P-Value
Temperature	2	10.594	67.25	10.594	5.2970	12.99	0.018
Time	2	3.529	22.40	3.529	1.7644	4.33	0.100
Error	4	1.631	10.36	1.631	0.4079		
Total	8	15.754	100				

Table 7. ANOVA for Transformed Response

Source	DF	Seq SS	Contribution (%)	Adj SS	Adj MS	F-Value	P-Value
Temperature	2	39975	50.31	39975	19987.4	29.15	0.04
Time	2	36744	46.24	36744	18372.1	26.79	0.05
Error	4	2743	3.45	2743	685.8		
Total	8	79462	100				

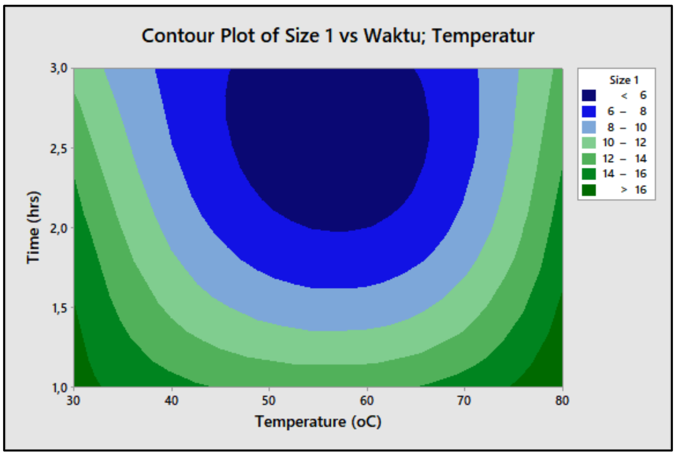


Figure 3. Independent Variables Correlation for SiO_2 Size

3.3. Analysis of Variance for SiO_2 Particle Size

The particle size of the sonicated SiO_2 is shown in Table 6. The smallest size of 5,303 nm, was obtained from the specimen with a temperature of 60°C and a sonication time of 3 hours. The ANOVA for SiO_2 particle size is presented in Table 7.

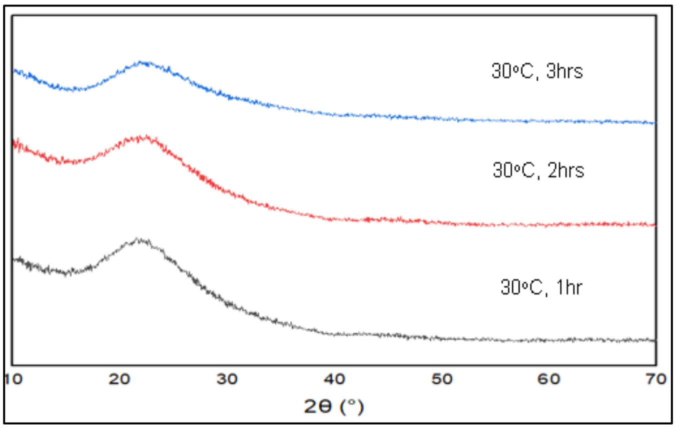
The independent variables, namely temperature and time, contributed to the particle size of 50.31% and 46.24%, respectively. Both of these variables significantly affect the particle size, as indicated by P-Value <5%, accounting for 0.004 and 0.005, respectively. With a 5% P-value, Ho is rejected and H1 is accepted. Therefore, it can be concluded that the independent variables have a significant effect on particle size. The error, representing variables outside the experimental parameters, is only 3.45%. This value is less than 5%, thus, it can be ignored. This small error value will affect the R-square value of 96.55%. An R-square value close to 1 indicates that the distribution of the data follows a reliable pattern.

The prediction of (SiO_2) size resulting from the correlation of independent variables shown in Fig. 3. It can be observed that the SiO_2 particle size below 6 nm can be obtained by adjusting sonication parameters, particularly with temperature ranging from 50 to 65°C and time between 2 and 3 hours. This contour plot facilitates easier way to choose DoE.

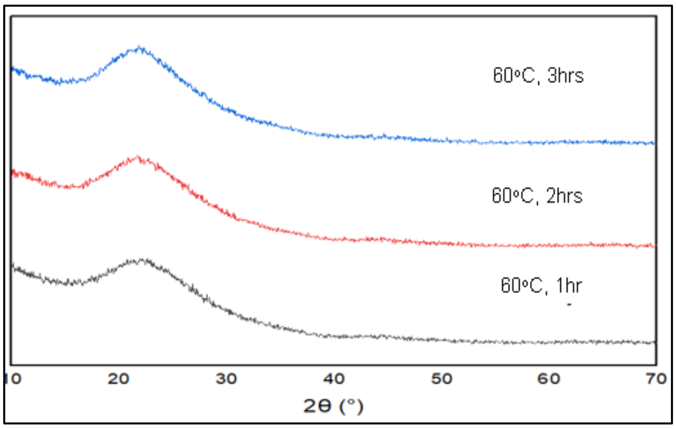
3.4. X-Ray Diffraction

The formed crystalline phase will be determined by the XRD test results. According to earlier investigations (Mourhly et al., 2015), the silica created during the synthesis process was amorphous silica. Fig. 4 presents the XRD results.

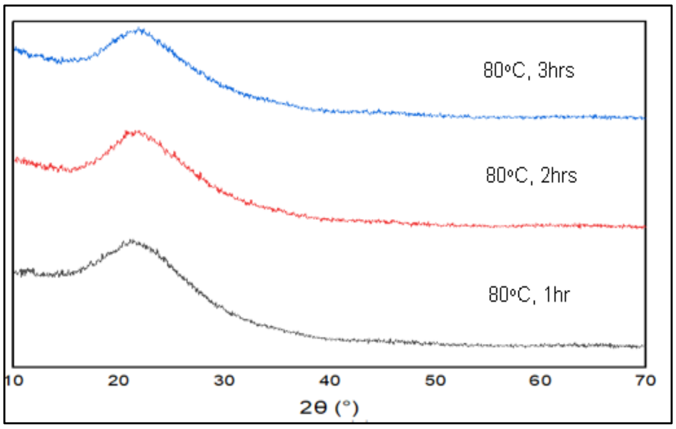
Pumice that has been ultrasonically processed at temperatures of 30, 60, and 80 °C for 1, 2, and 3 hours possesses amorphous silica. The amorphous phase can be identified by the shape of a diffractogram, which exhibits a curved pattern resembling a hill.



a). at 30 °C

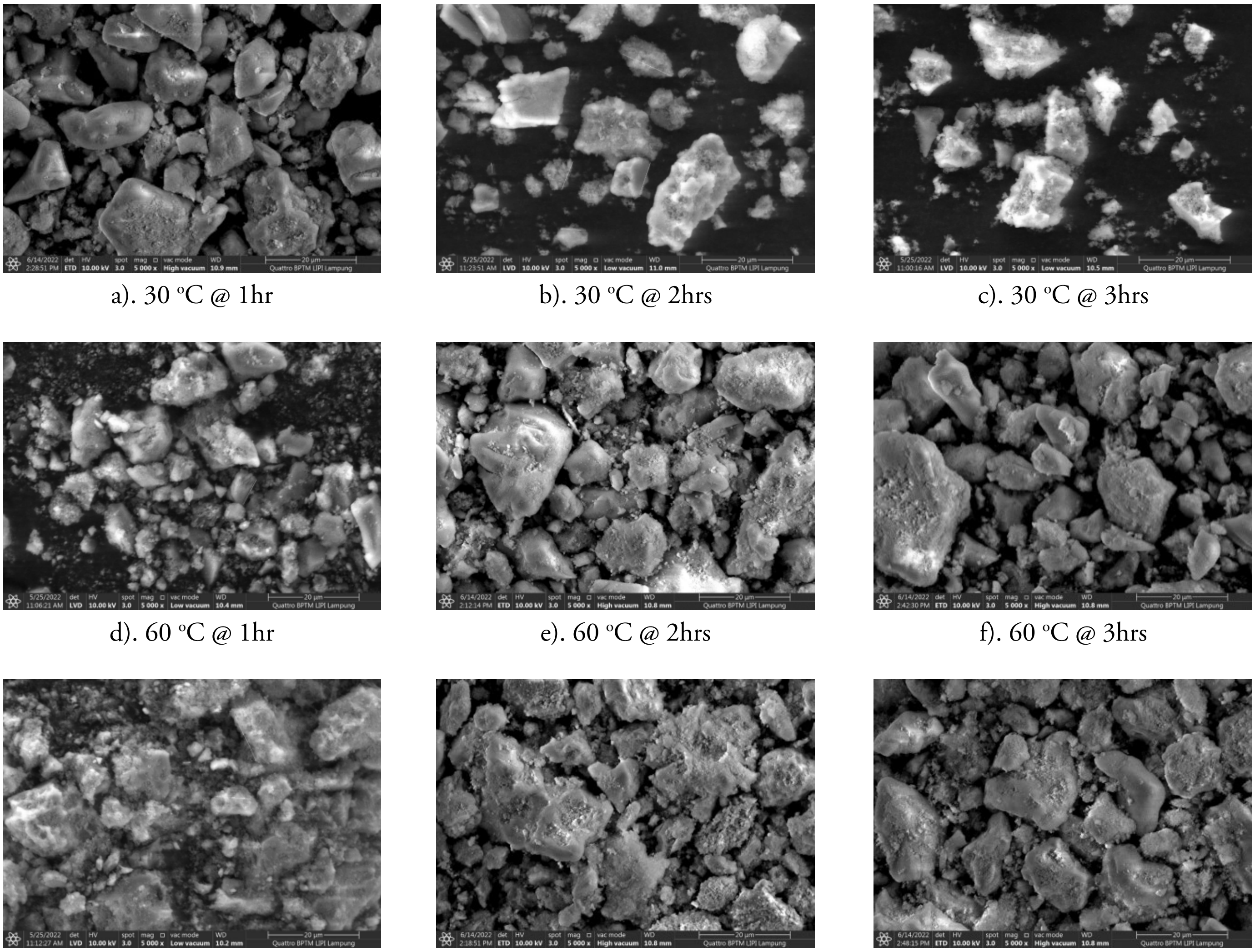


b). at 60 °C



c). at 80 °C

Figure 4. Comparison of Sonicated Silica Diffractogram



a). 30 ºC @ 1hr b). 30 ºC @ 2hrs c). 30 ºC @ 3hrs

d). 60 ºC @ 1hr e). 60 ºC @ 2hrs f). 60 ºC @ 3hrs

g). 80 ºC @ 1hr h). 80 ºC @ 2hrs i). 80 ºC @ 3hrs

Figure 5. Microphotos of Silica After Sonication

3.5. Nanoparticle Morphology Used SEM Image

Fig. 5 depicts the observation of photo micro silica following the sonication procedure. After processing the data from these microphotos, the particle size is determined.

Some of the silica particles have a sub-angular shape, which is characterized by acute angles on certain particles. The particles' surfaces appear rough and amorphous. The sonication process is also successful in producing nano-sized samples and can separate the agglomeration of particles like other research. The silica synthesis treatment using the sol-gel method, followed by the sonication process, did not induce changes in particle shape. It can be seen from the SEM image that the shape of the particles does not change significantly.

An increase in sonication temperature will enhance reaction kinetics in the sol-gel process. This heightened reactivity signifies accelerated hydrolysis and condensation reactions during silica formation. Furthermore, higher temperatures will also reduce the viscosity of the solution. Consequently, the lowered solutions' viscosity, improves the dispersion of silica particles. Therefore, higher temperatures contribute to better mixing and more uniform particle distribution. In this study three temperature variants were applied, ranging from room temperatures of 30ºC, 60ºC, to 80ºC. The SEM image reveals that the surface structure at a high temperature (80ºC) is rougher than at a low temperature. This rough surface indicates increased particle kinetic reactions in response to ultrasonic waves during particle agitation process . The surface conditions align with previous research, which noted that the sonication process at room temperature decreased micro-flotation. However, it's crucial to note that excessively high temperatures can lead to damage or degradation of the particle surface. Hence, selecting an appropriate process temperature is essential. Through Anova, the lowest process temperature can be selected in the predicted range to produce the most optimum size and composition of silica.

Purity, shape, and particle size are critical factors in determining the quality of silica nanoparticles. High purity of SiO_2, typically above 95%, ensures the use nano-silica without impurities from other ingredients. Silica nanoparticles are applicable in various fields, such as a filler or thickening agent in cosmetic products or as a catalyst. Electronic applications demand even higher purity, above 99%, as contaminants can adversely affect the performance of electronic devices. SiO_2 nanoparticle sizes below 10 nm are favorable for catalyst applications, while larger particle sizes around 90 nm, have been utilized as a filler for semiconductor packaging materials. Nanosilica measuring <7 nm was also reported to be successfully grafted with an amino group. The prediction chart from Anova simplifies the selection of parameters that comply particle size requirements.

Silica nanoparticles serve a crucial role in energy storage, acting as templates in making porous carbon for supercapacitor electrodes. Silica nanoparticles function as reinforcement, while increasing the hydrophilic properties of the interface on the surface of carbon pores. Another previous studies also affirmed that adding nano-silica increased the specific surface area of the supercapacitor electrode from 302 to 624 $F.g^{-1}$.

4. CONCLUSION

The pumice synthesis through modified sonication process has succeeded in obtaining amorphous silica particle with sizes ranging from 5,303 to 17,827 nm, achieving silica (SiO_2) purity between 94.24 - 98.97%. The independent variable, temperature, contributed 67.25% and exhibit a significant impact on the SiO_2 concentration. The two sonication variables, namely temperature and time, demonstrating a significant effect on particle size and contributed 50.31% and 46.24%, respectively. Additionally, there are other independent variables accounting for 10.36% that affect the SiO_2 concentration. The sonication process proves to be a reliable method for enhancing the concentration and particle size of the synthesized silica by selecting the appropriate independent variables.

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Tempeh Industry Wastewater Treatment using Mix Natural Adsorbents (Zeolite, Bentonite, Water Hyacinth-Activated Carbon): Effect of Mass Ratio and Dosage of Mix Adsorbents on Turbidity and pH

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ABSTRACT

Adsorption is the agglomeration of dissolved substances in solution by the surface of an absorbent substance, making the material enter and collect in an absorbent substance. Natural adsorbents that treat tempeh wastewater are mixed adsorbents that consist of zeolite, bentonite, and activated carbon made from water hyacinth. This study aimed to determine the effect of the mass ratio and dose of mixed natural adsorbents on tempeh wastewater's turbidity and pH values and the isotherm that occurred. The mass ratio variation used was the ratio of each material in the form of zeolite: bentonite: activated carbon in the form of R1 (1:1:1), R2 (2:1:1), R3 (1:2:1) and R4 (1:1:2). The adsorbent dose carried out was 1.5 gr; 3 grams; and 4.5 gr per 100 ml volume of wastewater. The contact time between the adsorbent and the wastewater is every 15, 30, 60, 90, 120, 150 minutes. Tempeh wastewater was processed in laboratory-scale batches with 120 rpm stirring. The primary analysis carried out is turbidity and pH. The results showed that the adsorption reduced turbidity and increased the pH level by processing the mass ratio R2 (2:1:1) for 150 minutes with a dose of 4.5 grams. It was found that the turbidity decreased by 99.5% from 520.5 NTU to 2.47 NTU, and the pH level increased from 3.7 to 6.4 after processing for 150 minutes at a dose of 4.5 grams. The maximum adsorption capacity validation results were obtained based on the Langmuir analysis of 8.26-10.61 mg/g with a constant of 0.27-6.4. These results show that mixed natural adsorbent is effective and potentially develops on tempeh wastewater treatment.

1. INTRODUCTION

Tempeh is a food source of vegetable protein consumed by Indonesian people. According to the Badan Pusat Statistik, the average per capita consumption of tempeh per week in 2022 is 0.140 kg (Badan Pusat Statistik, 2022). This food is made from fermented soybeans using yeast. The relatively economical price is also a factor in tempeh being one of the mandatory consumptions for Indonesian people, thus causing the tempeh-making industry to spread in various regions of Indonesia.

The wastewater from tempeh processing contains impurities that pollute the environment. Based on research from Cundari et al. (2022), tempeh wastewater contains some pH, turbidities, Total Suspended Solid (TSS), Chemical Oxygen Demand (COD), and Biological Oxygen Demand (BOD which is shown in Table 1. Based on The Minister of Environment and Forestry of The Republic of Indonesia Regulation No. 5 (2022), wastewater food processing should be at most the maximum standard. In addition, tempeh wastewater needs treatment for decreasing the pollution before being discharged into the environment.

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Trisnadewi et al. (2017) treated tempeh waste using natural zeolite. Treatment is carried out to decrease BOD and COD from tofu industrial wastewater. Before use, natural zeolite was activated using HCl 6 N and NH4NO3 N. The result was then calcined at 300°C. The results showed that the decrease in BOD has best decreased on 1.5 gr mass variation dosed, with an efficiency of 85.7%, while the decrease in COD was 35.7%. Natural zeolite has several weaknesses, including impurities such as Na^+, K^+, Ca^{2+}, Mg^{2+}, and Fe^{3+}, and its crystallinity could be better. The presence of these impurities will reduce the activity of natural zeolite (Setiawan et al., 2018). It is necessary to activate or modify the natural zeolite first to improve its character before using it as an adsorbent, catalyst, or application so that the activity increases (Darojah et al., 2018).

Maulani et al. (2021) treated tempeh waste using bentonite and PAC, resulting in a 53% TSS removal and a 95% reduction in TDS. In addition, the values of BOD and COD can decrease significantly, namely BOD of 87% and COD of 84%. The resulting bentonite had limited adsorption ability, which can be overcome through an activation process using acids, and is classified as a strong acid, causing a decrease in effectiveness, resulting in bentonite with a higher adsorption capacity (Kumar et al., 1995).

It is very possible to combine zeolite and bentonite for tempeh wastewater. Zeolite and bentonite can be easily found cheaply and are not harmful to the environment. In this research, water hyacinth-based activated carbon will be added. Using water hyacinth-based activated carbon can reduce water hyacinth, which is excessive and can pollute the environment. This research aims to get the turbidity and pH removal data on tempeh wastewater by using a mixed natural adsorbent and analyzing the isotherm that occurred.

2. METHODS

2.1. Preparation of Adsorbent as Raw Materials and Collection of Tempe Waste

The water hyacinth-based activated carbon was produced by pyrolysis at 600°C for 3 hours (Cundari et al.,2023). Zeolite and bentonite are technical-grade materials that were obtained from online stores. The materials were washed using clean water to remove the contaminants. The washed materials were dried. Tempe wastewater was obtained from one of the tempeh productions in a tempeh factory on Jl. Macan Lindungan Perumahan Kopti, Pabrik Tempe Kopti, Palembang, Indonesia.

2.2. Preparation and Activation of Zeolite

Zeolite was crushed into 100 mesh and then washed with distilled water before being dried in an oven at 110°C for 3 hours. Then, it will be activated with 0.4 M HCl laurate as an activator with magnetic stirring on a stirrer in a 250 ml Erlenmeyer covered with aluminum foil for 4 hours at a speed of 100 rpm (Lestari, 2018).

Then, the zeolite will be calcined with a muffle furnace at 500°C for 5 hours (Lestari, 2018). The zeolite that has been calcined will be filtered and washed using distilled water so that the pH becomes neutral.

2.3. Preparation of Water Hyacinth-based Activated Carbon

The water hyacinth used in this study is part of the stems and leaves. Then, washing with water, distilled water, and soaking in a solution of 0.25 M Ethylene diamine tetra acetic acid at pH 10 for 24 hours to remove the metal ion content in the plants. The active carbon was washed three times using distilled water and dried in an oven at 110°C for 48 hours. The dried active carbon was then reduced in size to 100 mesh.

Active carbon biosorbent was impregnated in 1 M H_3PO_4 solution with a ratio of 3:1 for two days at room temperature, then dried in an oven at 110°C for 3 hours. Then, it is put into the muffle furnace, where a pyrolysis process occurs with little/no oxygen at 600°C for 3 hours (Cundari et al.,2023). The activated carbon that has been calcined will be rewashed using aquadest so the pH is neutral.

2.4. Preparation and Activation of Bentonite

Bentonite was crushed with a porcelain mortar and sieved with a size of 100 mesh. The resulting bentonite was weighed 50 g, soaked with 500 mL of 0.8 M H_2SO_4 in 1000 mL Erlenmeyer, covered with aluminum foil, and shaken at 9 rpm for 3 hours (Rizqullah, 2018). The immersion samples were washed with aquadest until SO_4^{2-} was no longer present. It can be known by the universal pH, which shows the pH according to aquadest. Samples were dried in an oven at 110°C for 2 hours, and then the bentonite solution was calcined for 5 hours at 500°C.

2.5. Experimental Procedure

The results were analyzed to validate the results obtained only on the best samples. The variations were analyzed starting from pH and turbidity to get the best data. The analysis was carried out up to two repetitions. After obtaining the initial waste sample analysis, then carry out the adsorption process using a mix of natural adsorbents (zeolite: bentonite: activated carbon) with variations R1 (1:1:1), R2 (2:1:1), R3 (1:2:1), R4 (1:1:2) with a dose of (1.5; 3.0; 4.5) gram/100 ml of tempeh wastewater.

The adsorption process was carried out using a stirrer with a speed of 120 rpm. Stirring time was 15, 30, 60, 90, 120, 150 minutes. The sample was then allowed to stand for 15 minutes so that the residual adsorbent could precipitate. Waste that has gone through filtration was analyzed for pH levels and turbidity values for two repetitions. Turbidity is a relative measure that determines water clarity. The more apparent the water, the lower the turbidity value. It is because light can penetrate to the bottom of the water. The power of hydrogen (pH) value is the degree of acidity of a solution. This value is the sum of the hydrogen ion concentrations in a solution. pH and Turbidity values are parameters that will be reviewed in this study.

The results of research on each variation were done. The stirred sample was then filtered using filter paper, and the remaining adsorbent that had been filtered was put into the oven heated to a temperature of 110°C for 2 hours. The turbidity data was used to calculate the isotherm that occurred as Langmuir of Freundlich isotherm.

2.6. Analysis Procedure

2.6.1. Turbidity, pH, TSS, COD, and BOD analysis

The analysis was conducted at the Palembang Health Laboratory Center (BBLK), which KAN certified. Turbidity analysis was carried out using the SNI 06-6989.25-2005 method. pH analysis was carried out using the SNI 6989.11.2019 method. Total Suspended Solid (TSS) analysis was performed using the Gravimetric method. Chemical Oxygen Demand (COD) analysis was carried out using the Spectrophotometric method. Biological Oxygen Demand (BOD) analysis was done using the Manometric method.

Table 1. Analysis of initial tempeh wastewater (Cundari et al., 2022)

Parameter	Units	Result of Analysis	Standard
pH	-	4,69	6 – 9
Turbidity	NTU	209	-
TSS	mg/L	0,3	200
COD	mg/L	431	300
BOD	mg/L	228	150

Table 2. Tempe Wastewater Water Analysis Results Before Processing

Parameter	Units	Analysis Result	Method	Environmental Quality Standards
pH	-	3.9	SNI 6989.11 : 2019	6 – 9
Turbidity	NTU	511.5	SNI 06-6989.25 - 2005	25
TSS	mg/L	1042	Gravimetric	200
COD	mg/L	791	Spectrophotometry	300
BOD	mg/L	97	Manometry	150

3. RESULT AND DISCUSSION

The sample of wastewater from the tempeh industry used in this study was from washing soybeans in tempeh production in Jl. Macan Lindungan Perumahan Kopti, Pabrik Tempe Kopti, Palembang, Indonesia. Before starting the waste treatment, samples were first analyzed for pH, turbidity, Total Suspended Solid (TSS), Chemical Oxygen Demand (COD), and Biological Oxygen Demand (BOD), as seen in Table 2.

The waste generated from tempeh producers was analyzed first. It referred to the Regulation of the Minister of Environment of the Republic of Indonesia No. 5 of 2022 concerning Wastewater Quality Standards for Soybean Processing Businesses or Activities. The results of the analysis on wastewater did not meet quality standards where several parameters exceeded the maximum value, which is harmful to the environment. It resulted from an analysis of tempeh wastewater at The Health Laboratory Center (BBLK) Palembang.

3.1. Turbidity Removal

Turbidity can be caused by various factors, including organic and inorganic materials in the water, such as soybeans, which participate in the soaking process, and microbes. These pollutants can make natural waters more turbid and even form sediment. High turbidity strongly influences the concentration of dissolved oxygen present in the water. The effect of increasing turbidity is reducing the penetration of external light that enters the water. Turbidity can limit light in water due to the attractive force of attraction between molecules that occurs due to objects touching each other (Azhari, 2016).

3.1.1. Turbidity in Adsorbent R1 Ratio (1:1:1)

Variations in the ratio of adsorbent mixture R1 were using a mass ratio of 1:1:1 from zeolite, bentonite, and active carbon. The results from the use of doses at various ratios of the R1 adsorbent mixture in reducing turbidity are shown in Figure 1.

Based on Figure 1, using this mix ratio, the decrease in turbidity has a very significant decrease, from 511,5 NTU to 29.3 NTU. The adsorption occurred fast in the first 15 minutes and reached equilibrium. The time and dosage used during the stirring process affect the reduction percentage. The longer the contact time and the greater the adsorbent dose, the greater the effectiveness of reducing turbidity.

The average percentage of turbidity reduction in this mixture is 88%. It was concluded that this mixture was less effective than other mixtures, with a more than 90% percentage, and needed to meet environmental quality standards.

3.1.2. Turbidity in Adsorbent R2 Ratio (2:1:1)

The use of variations in the ratio of adsorbent mixture R2 using a mass ratio of 2:1:1 from zeolite, bentonite, and active carbon effectively reduced the turbidity parameter, as shown in Figure 2.

Based on Figure 2, the adsorbent mixed ratio, where the adsorbent in zeolite, was used predominantly in this study with a dose variation of 2:1:1 for every 1.5, 3, and 4.5 grams. The decrease in turbidity that occurred experienced a very significant decrease. The decrease was more effective than the previous mixture ratio, where the turbidity value decreased by approximately 99.5% from the initial level (from 511.5 NTU to 2.475 NTU). The number of doses or the long contact time did not significantly affect the percentage of turbidity.

The optimum value was obtained at 15 minutes of stirring at a dose of 4.5 grams with a decrease of 511.5 NTU to 8.895 NTU with a reduction effectiveness of 98%. The maximum value obtained in this mixture was obtained at a dose of 4.5 grams with a stirring time of 150 minutes. It obtained a decrease from 520.5 NTU to 2.475 NTU with a reduction effectiveness of 99.5%. The average percentage of turbidity reduction is 97%. This mixture has the best percentage of the other mixed variations.

The research results of (Mulia et al., 2022) in reducing turbidity values used a mixture of rice husks, coconut shell charcoal, zeolite, and quartz sand. The results obtained for turbidity decreased from the value before filtration of 1153 NTU to 104 NTU (90.98%). The dosage variations of the adsorbent used were higher than in this research, but the results obtained were lower than in this research.

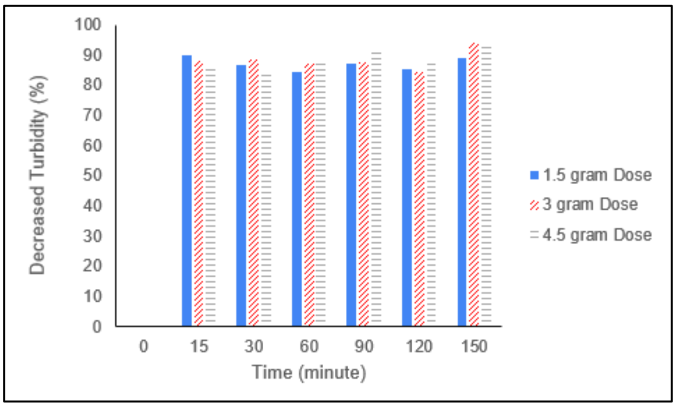


Figure 1. Turbidity reduction of tempeh wastewater at variations in the mass ratio R1

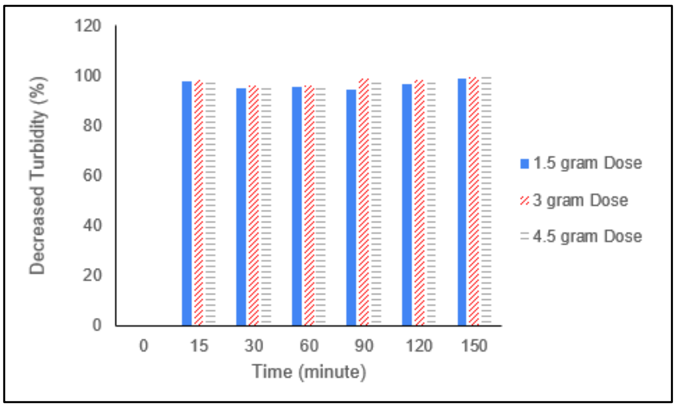


Figure 2. Turbidity reduction of tempeh wastewater at variations in the mass ratio R2

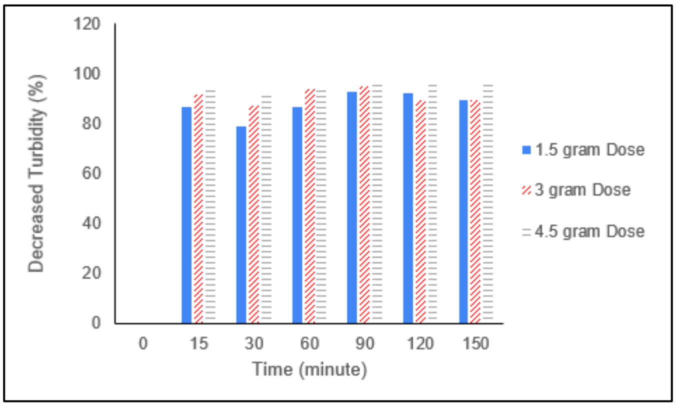


Figure 3. Turbidity reduction of tempeh wastewater at variations in the mass ratio R3

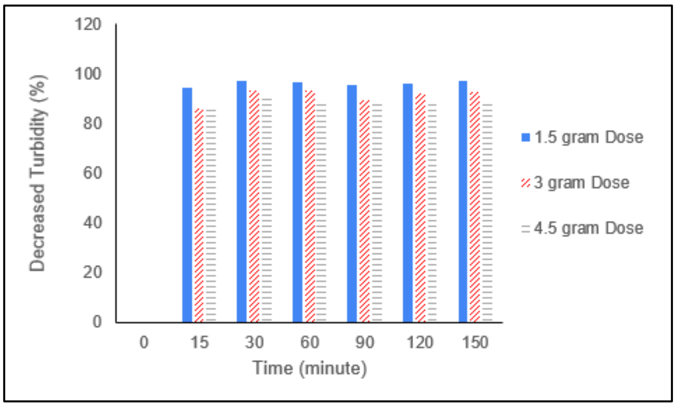


Figure 4. Turbidity reduction of tempeh wastewater at variations in the mass ratio R4

3.1.3. Turbidity in Adsorbent R3 Ratio (1:2:1)

This method used variations in the ratio of the adsorbent mixture R3 using variations in mass ratio of 1:2:1 from zeolite, bentonite, and activated carbon. The following results from using doses at various ratios of the adsorbent mixture R3 in reducing the turbidity parameter are shown in Figure 3.

Based on Figure 3, variations in the ratio of the adsorbent mixture R3 where the adsorbent in bentonite was used predominantly in this study with a dose variation of 1:2:1 for every 1.5; 3; 4.5 grams. Based on Figure 3, the contact time during the mixing process did not significantly reduce turbidity. However, the number of doses does have a significant effect during the process. The more doses used, the better the effectiveness of reducing turbidity.

The optimum value was obtained at 15 minutes of stirring at a dose of 4.5 grams with a decrease of 511.5 NTU to 30.85 NTU with a reduction effectiveness of 93%. The maximum value obtained in this mixture was obtained at a dose of 4.5 grams with a stirring time of 90 minutes. An impairment loss of 488.5 NTU was obtained to 14.73 NTU with a reduction effectiveness of 97%. The average percentage of turbidity reduction is 91%. This mixture has a better percentage than the R1 but is less effective than the R2 mixture.

3.1.4. Turbidity in Adsorbent R4 Ratio (1:1:2)

This method used variations in the ratio of the adsorbent mixture R4 using variations in the mass ratio of 1:1:2 from zeolite, bentonite, and active carbon. The following results from the use of doses at varying ratios of the R4 adsorbent mixture in reducing turbidity levels are shown in Figure 4.

Based on Figure 4., variations in the R4 mixture ratio where the adsorbent in the form of active carbon activated carbon was used dominantly in this study with a dose variation of 1:1:2 for every 1.5; 3; 4.5 grams. In using this mixed variation, the decrease in turbidity experienced a very significant decrease. Based on Figure 4, the contact time during the process did not significantly affect the decrease in turbidity. Judging from the addition of adsorbent doses, the effectiveness of reducing turbidity has a better value at a dose of 1.5 grams of adsorbent compared to other doses.

The optimum value was obtained at 15 minutes of stirring at a dose of 1.5 grams with a decrease of 511.5 NTU to 30.5 NTU with a reduction effectiveness of 94%. The maximum value was obtained at a dose of 1.5 grams with a stirring time of 30 minutes, obtaining a decrease from 506.5 NTU to 14.87 NTU with a reduction effectiveness of 97%. The average percentage of turbidity reduction was 91%. This mixture has the same percentage as the R3 mixture, better than R1, but less effective than the R2 mixture.

Research conducted by Cundari et al. (2022) used the active carbon adsorbent of water hyacinth as much as the adsorbent in tempeh wastewater. The results showed that turbidity decreased to 81% from the initial level. Compared to the research conducted, the effectiveness is much better because of the effect of the addition of a mixture of zeolite and bentonite in reducing turbidity in waste. The results showed that the adsorption process with variations in the ratio of the R4 adsorbent mixture reduced turbidity according to environmental quality levels.

3.2. The Effect of the Adsorption Process on the PH Value of Wastewater

Industrial waste from tempeh is usually acidic, and volatile substances are easily released in this acidic state. These substances can cause an unpleasant odor from the tempeh industrial wastewater. pH has a significant impact on water treatment processes. The quality standard of the pH is 6-9. The effect that occurs when the pH is too low is reduced dissolved oxygen. Suparno et al. (2020) state that the long immersion treatment factor significantly affects pH. The longer the contact time in waste treatment, the better the pH level will be.

3.2.1. pH in Adsorbent R1 Ratio (1:1:1)

The following results from varying doses of the R1 adsorbent mixture ratio in stabilizing pH levels are shown in Figure 5.

Based on Figure 5, the effectiveness of adsorption in raising the pH increases every minute during the stirring process. At each dose, stirring at 15 minutes had not reached the pH standard according to quality standards. The new pH level exceeded the quality standard when the stirring time was 30 minutes for each dose of adsorbent mass except for the 1.5-gram dose, which has yet to reach the standard for tempeh wastewater.

The optimum value for this mixture was obtained at a stirring time of 60 minutes, one of which was at a dose of 4.5 grams, with an increase in value reaching 6.4 with an increase in effectiveness of 62%. The maximum value obtained for this mixture was obtained at a dose of 4.5 grams with a time stirring of 150 minutes. The increase in pH occurred at the initial level value of 3.82 to 6.6 with an effective increase of 72%, which is almost close to the neutral pH.

The average increase that occurred in the mixed variation R1 was 62%. The results showed that the adsorption process with a mixture ratio of R1 had the best effectiveness of the four variations of other natural adsorbent mixtures and had achieved standardization of environmental quality standards.

3.2.2. pH in Adsorbent R2 Ratio (2:1:1)

The following results from varying doses of the R2 adsorbent mixture ratio in stabilizing pH levels are shown in Figure 6.

Based on Figure 6, the pH value at each stirring time increased gradually. Of the three doses, only the two doses experienced an increase in pH according to the pH standardization target at a stirring time of 120 minutes. The 3-gram dose reached the standardization line at a stirring time of 60 minutes, while the 4.5-gram dose had only reached the target at 120 minutes. The 1.5-gram dose experienced a less effective increase because it had yet to reach the pH standardization target according to the maximum stirring time.

The optimum value for this mixture was obtained at a stirring time of 90 minutes, one of which was at a dose of 3 grams with an increase in value reaching 6.4 with an increase in effectiveness of 67%. The maximum value obtained for this mixture was obtained at a dose of 3 grams with a stirring time of 150 minutes. The increase in pH occurred at the initial level value of 3.82 to 6.6 with an effective increase of 72%, which is almost close to the neutral pH.

The average increase in the mixed variation of R2 was 53%. The results showed that the process with a variation of the adsorbent mixture R2 could stabilize the pH according to environmental quality levels. However, it was not very effective compared to the variation of the R1 mixture.

3.2.3. pH in Adsorbent R3 Ratio (1:2:1)

The following results from varying doses of the R3 adsorbent mixture ratio in stabilizing the pH are shown in Figure 7.

Based on Figure 7, the increase in pH had a less significant increase each time of stirring. The three total doses had yet to reach the pH standardization target according to environmental quality standards. The 3-gram dose has the most stable increase compared to the other three doses and almost melts the pH standardization target according to quality standards.

The optimum value for this mixture was obtained at a stirring time of 60 minutes, one of which was at a dose of 3 grams with an increase in value reaching 5.5 from the initial concentration with an increased effectiveness of 43%. The maximum value obtained for this mixture was obtained at a dose of 3 grams with a stirring time of 150 minutes. The increase in pH occurred at the initial level value of 3.82 to 5.8 with an increased effectiveness of 49%, which is still below the pH target.

The average increase in the mixed variation of R3 was 44%. The results showed that the adsorption process with the ratio of the adsorbent mixture R3 was not able to increase the pH according to the environmental quality levels and was a less effective mixture variation compared to the other three mixtures.

3.2.4. pH in Adsorbent R4 Ratio (1:1:2)

The following results from varying doses of the R4 adsorbent mixture ratio in stabilizing the pH are shown in Figure 8.

Based on Figure 8, the increase in pH did not experience a significant increase compared to the R1 and R2 mixture variations but was better than the R3 variation. Based on all the doses tested, only the 4.5-gram dose reached the pH standardization target according to environmental quality standards with a stirring time of 150 minutes. The 1.5-gram and 4.5-gram doses experienced an ineffective increase each time the stirring was carried out and had yet to reach the pH standardization target.

The optimum value for this mixture was obtained at a stirring time of 90 minutes, one of which was at a dose of 4.5 grams, with an increase in value reaching 5.7 from the initial concentration with an increased effectiveness of 49%. The maximum value obtained for this mixture was obtained at a dose of 4.5 grams with a stirring time of 150 minutes. The increase in pH occurred at the initial level value of 3.82 to 6.1 with an effective increase of 59%, which has reached the standardization target but is still far from being neutral (7).

The average increase in the mixed variation of R4 was 43%. The results showed that the adsorption process with a variation of the R4 mixture stabilized the pH according to environmental quality levels with only a dose of 4.5 grams at 150 minutes of stirring. This mixture is less effective than the R1 and R2 mixture variations. However, it is better than the R3 mixture.

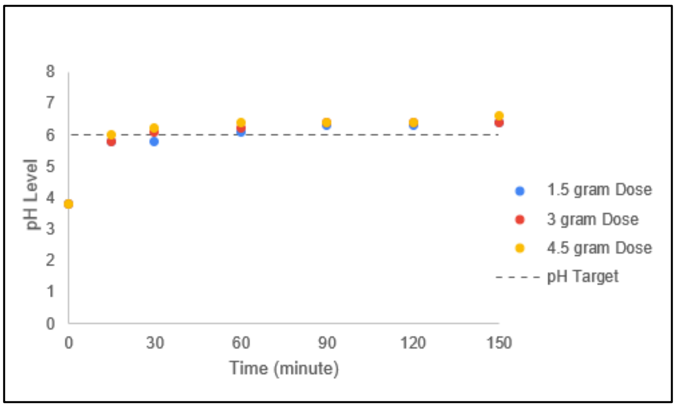


Figure 5. The pH value of tempe wastewater on variations in the mass ratio of R1

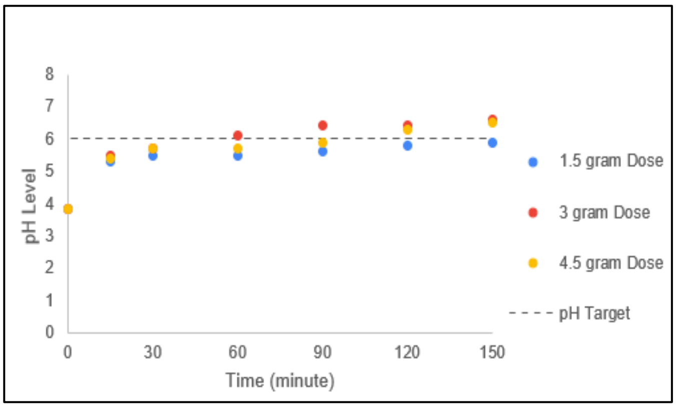


Figure 6. The pH value of tempe wastewater on variations in the mass ratio of R2

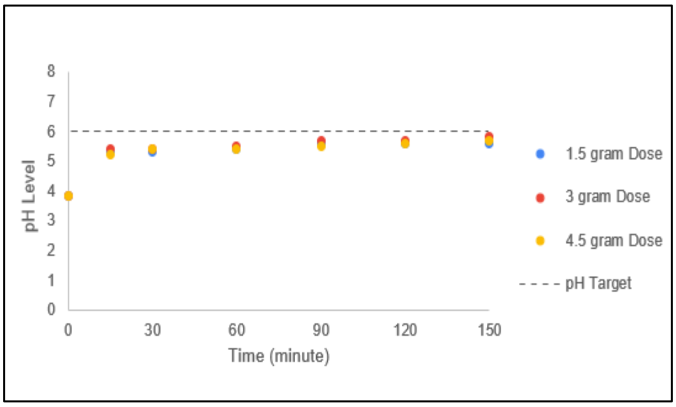


Figure 7. The pH value of tempe wastewater on variations in the mass ratio of R3

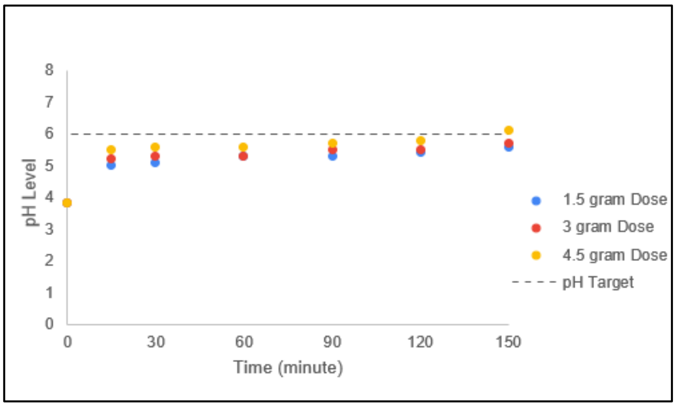


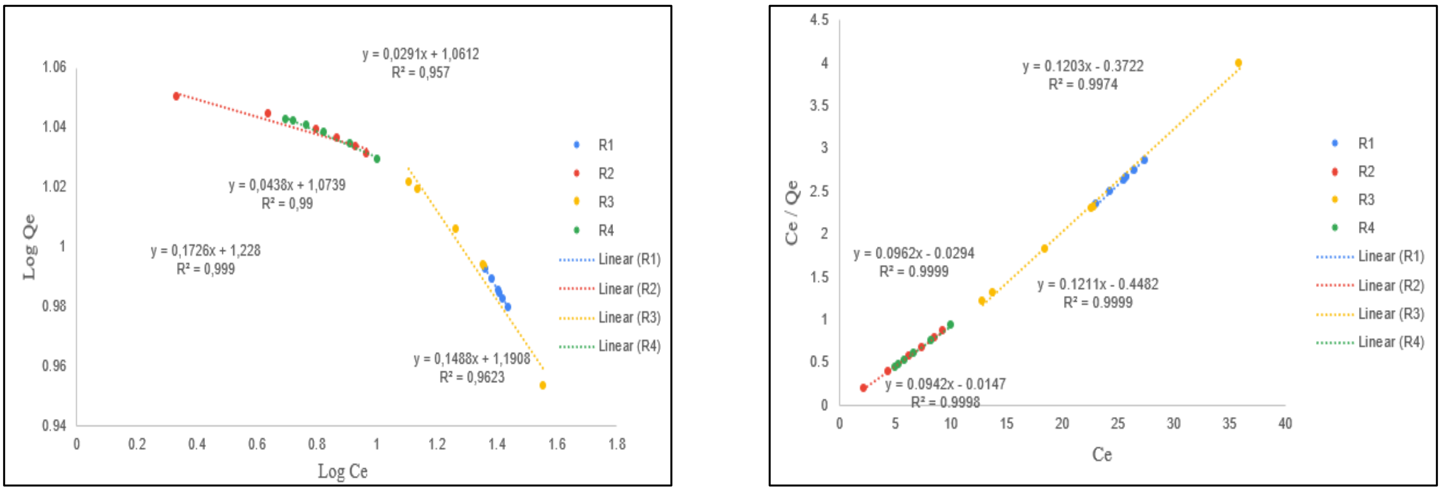
Figure 8. The pH value of tempeh wastewater on variations in the mass ratio of R4

3.3. Adsorption Capacity of Natural Adsorbents

Determination of the adsorption capacity value aims to determine the ability of the adsorbent to bind components in managing tempeh wastewater. These can be seen in Figures 9, 10, and 11 below the Langmuir and Freundlich isotherm graph.

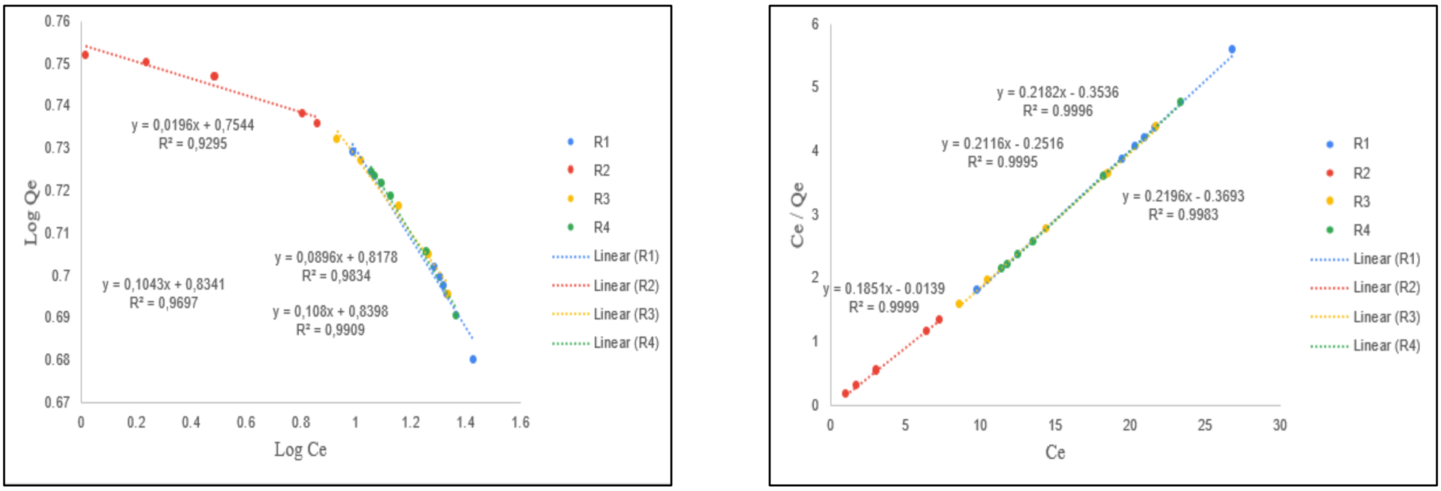
Based on the analysis using the Freundlich and Langmuir adsorption model, the regression results for each mixture variation are almost close to 1 so that it can be used to analyze the adsorption process because the square of the regression is close to 1 (Wijayanti et al., 2018). Analysis of the Freundlich isotherm results on tempeh waste with a dose of 1.5 grams had a maximum capacity of 3.43-22.83 mg/g with a Freundlich constant of 1.06-1.22 l/mg. A dose of 3 grams has a maximum capacity of 9.26-51.02 mg/g with a Freundlich constant of 0.75-0.83 l/mg. A dose of 4.5 grams has a maximum capacity of 7.07-49.75 mg/g with a Freundlich constant of 0.67-0.70 l/mg.

Analysis of the Langmuir isotherm results in tempeh waste with a dose of 1.5 grams with a maximum capacity of 8.26-10.61 mg/g and a Langmuir constant of 0.27 - 6.40 l/mg. A dose of 3 grams has a maximum capacity of 4.55-5.40 mg/g with a Langmuir constant of 0.59 – 13.31 l/mg. A dose of 4.5 grams has a maximum capacity of 2.90-3.57 mg/g with a Langmuir constant of 0.38 – 10.89 l/mg. It can be concluded that the maximum adsorption capacity based on Langmuir analysis is 8.26-10.61 mg/g with a Langmuir constant of 0.27-6.40 l/mg, which was obtained at a dose of 1.5 grams.



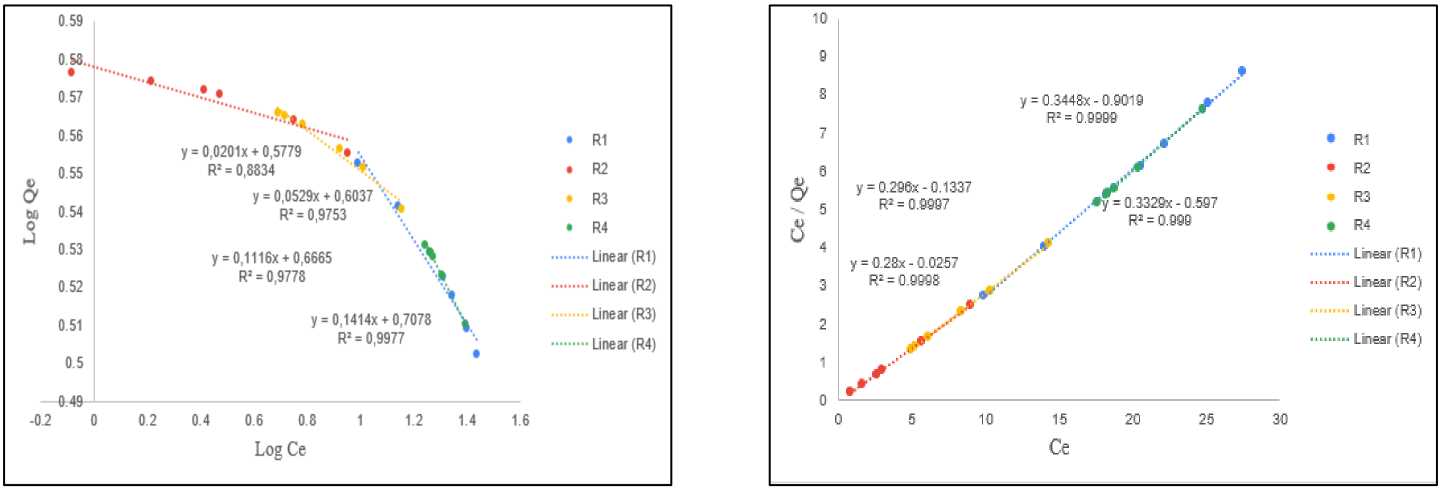
(a) (b)

Figure 9. Isotherms at a Dose of 1.5-gram (a) Langmuir Isotherm, and (b) Freundlich Isotherm



(a) (b)

Figure 10. Isotherms at a Dose of 3-gram (a) Langmuir Isotherm, and (b) Freundlich Isotherm



(a) (b)

Figure 11. Isotherms at a Dose of 4.5-gram (a) Langmuir Isotherm, and (b) Freundlich Isotherm

Table 3. Comparison of Analysis Results of Tempe Waste Samples Before and After the Adsorption Process

Parameters	Before Adsorption	After Adsorption (optimum condition, 15 minutes adsorption)			
	First Sample	R1	R2	R3	R4
pH[1]	3.9	5.4	5.8	6.0	5.7
pH[2]	3.8 – 3.9	5.8 – 6.6	5.3 – 6.5	5.3 – 5.7	5 – 6.1
Turbidity[1] (NTU)	511.5	33.400	23.200	24.100	–
Turbidity[2] (NTU)	488.5 - 521	82.35 – 29.3	27.85 – 2.47	68.55 –11.35	74.2 – 9.44
TSS[1] (mg/L)	1042	794	723	702	–
COD[1] (mg/L)	791	437	369	191	–
BOD[1] (mg/L)	97	80	69	58	–

(*1 Analysis Result at BBLK, *2 Analysis Result at Separation and Purification Laboratory)

3.4. Comparison of Optimum Results after Adsorption

Based on the research, the waste treatment results were carried out using various natural adsorbents, where the pH, turbidity, TSS, COD, and BOD values were tested at the Palembang Health Laboratory Center. There were several tests on a small laboratory scale in the form of pH and Turbidity, which were tested at the Separation and Purification Laboratory of Universitas Sriwijaya. The results of the analysis are presented in Table 3. The samples that were analyzed after adsorption was the optimum sample that occurred at 15 minutes of operation.

Based on Table 3. tempeh wastewater treatment was more effective at every variation of adsorbent ratio. R2 dose at 15 minutes of stirring time reduced turbidity to 95.3% from 557.91 NTU to 24.100 NTU. However, these results were not significantly different from the R2 dose, with a yield of 23.200 NTU with a reduction percentage of 95.46%. R3 had an effective concentration level increase at the pH value compared to other dose variations, where the percentage increase is 53.84% from 3.9 to 6.0. The TSS value can be reduced by up to 33.26% from 1042 mg/L to 702 mg/L. This value still needs to be able to pass the waste disposal quality standard value. The high and low TSS and turbidity values are not always linear. The particles that cause water turbidity can consist of particles with different properties and weights, so they are not included in the comparable TSS residual weight (Fatimah, A. 2014). The COD value can be reduced to 75.85% from 791 mg/L to 191 mg/L at R3. The BOD value can be reduced to 40.20% from 97 mg/L to 58 mg/L. The sample with variation R4 was not analyzed because the turbidity and pH data showed less removal than the others.

The results obtained from the analysis of the two different places have several differences that are not significant. The difference is from the research results that have been done before and are being done now. Table 3 shows that the adsorption process in these studies reduced turbidity, TSS, COD, and BOD up to 95%, 33%, 76%, and 40%, respectively. Research conducted by (Novita et al., 2019) reduced turbidity by 85.03% and BOD by 77.91% in processing tempeh wastewater using active carbon.

Research conducted by (Lia Cundari et al., 2022) resulted in the highest percentage of TSS reduction, namely 73% in the processing of tempeh wastewater using active carbon. The highest percentage of COD reduction, 89.3%, was obtained in a study by Widianti et al. (2022) in processing Tempe wastewater using natural zeolite. The comparison of research results can be seen in Table 4.

4. CONCLUSION

Adsorption using a mixture of natural adsorbents can reduce turbidity in tempeh wastewater and increase the pH. The best percentage was the removal of 99% turbidity and a pH level of 6.5 at the mass ratio R2 with 150 minutes of stirring at a dose of 4.5 grams. Adsorption using a variety of natural adsorbents can stabilize some of the impurities under standard parameters of environmental quality standards. Adsorption of Tempeh waste with a mixture of zeolite, bentonite, and active carbon adsorbents follows the Langmuir isotherm. The maximum adsorption capacity was

8.26-10.61 mg/g with a Langmuir constant of 0.27-6.40 l/mg.

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Transforming The Furniture Industry in The Digital Age

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ABSTRACT

The furniture industry is experiencing a significant transition driven by digital technologies. This article comprehensively reviews various technologies, techniques, and innovations the furniture industry adopts to enhance efficiency, sustainability, and competitiveness. The analysis draws on a systematic literature review of recent publications in ScienceDirect and Scopus databases. The study highlights the potential of automation, robots, augmented reality, and the Internet of Things to improve the furniture production process, reduce waste, and boost profitability. Additionally, the article examines technologies and approaches that can help the furniture industry become more sustainable and socially responsible, such as green supply chain management, life cycle assessment, and ergonomic treatments. The paper concludes by advocating for a comprehensive digital transformation strategy that includes embracing new technologies, developing innovative business models, and promoting sustainability and ethical standards.

1. INTRODUCTION

The furniture industry has undergone considerable changes, including technological breakthroughs, globalization, and shifting consumer preferences. The sector has recently encountered problems such as environmental concerns (Teng et al., 2023), supply chain interruptions (Caridi et al., 2012; Hisjam et al., 2015; Susanty et al., 2016), and increased competition (Carpano et al., 2006), necessitating reform to maintain long-term survival.

The need for greater sustainability is a significant challenge for the furniture sector, including lowering environmental effects, encouraging social responsibility, and guaranteeing economic viability (Feil et al., 2015). Furthermore, the industry must handle worker safety, supply chain management, and product quality concerns (Hisjam et al., 2015). To achieve these objectives, embracing technological breakthroughs, applying new initiatives, and executing best practices are necessary.

This review article aims to look into several technical breakthroughs, tactics, and best practices that can be used to alter the furniture sector in the digital age. The article will discuss many techniques for addressing industrial difficulties, such as enhancing sustainability, worker safety, supply chain management, and product quality. The paper will also discuss the benefits and drawbacks of different approaches and recommendations for their implementation.

Product modularity and innovation are critical strategies for improving supply chain performance (Caridi et al., 2012). This method enables businesses to design

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products with modular components that can be easily adjusted to match the needs of specific customers. This method can lower production costs, increase efficiency, and boost customer satisfaction. Therefore, significant investments in research and development are required (Michalski, 2015).

Global value chains have been demonstrated to promote competitiveness and upgrading in the furniture business (Epede & Wang, 2022). This strategy entails integrating various value chain stages across many geographies, allowing enterprises to enter new markets, cut costs, and boost competitiveness. However, to guarantee efficient adoption, extensive coordination and administration are required (Colak et al., 2015).

Automatic control is another strategy that has been found to improve precision and efficiency in the furniture sector (Teng et al., 2023). It entails using automated technology to control manufacturing, decrease human error, and enhance efficiency. This strategy can potentially increase quality while lowering manufacturing costs, but it necessitates significant investments in technology and infrastructure.

Ergonomics in analyzing work stress and its effects on workers has been identified as critical in guaranteeing worker safety in the furniture business. This method can assist in identifying potential risks and providing remedies to lessen the chance of injury. Nonetheless, significant investments in training and equipment are required. The furniture sector faces several issues requiring reform to assure long-term viability. Implementing technological advances, new techniques, and best practices can assist in addressing these issues.

In recent years, the furniture industry has witnessed a significant transformation, predominantly driven by the adoption of digital technologies. Central to this revolution has been the integration of Computer Numerical Control (CNC) machinery in production, which has enabled unprecedented precision and efficiency (Koc et al., 2017; Rabiei & Yaghoubi, 2023). CNC machines have allowed complex designs to be executed precisely, minimizing human error and reducing waste materials (Kaba et al., 2023). It has led to cost savings and expanded the possibilities for custom furniture design, catering to a market that increasingly values uniqueness and personalization.

Alongside production enhancements, 3D modelling software has redefined the design process within the furniture industry (Caeiro et al., 2022; Falheiro et al., 2022; Tikul et al., 2022). Designers are now equipped to create and modify intricate product models digitally, which can be visualized in virtual environments, allowing for rapid prototyping and iteration (Andrikos et al., 2023; Nijdam et al., 2022; Werner et al., 2021). This shift has significantly reduced the time from concept to market, fostering a culture of innovation and agile response to consumer trends.

Furthermore, Enterprise Resource Planning (ERP) systems have brought about a new era of supply chain management (Chopra et al., 2022; Lengnick-Hall et al., 2004). By integrating all facets of operations, from inventory management to customer relations, ERP systems provide a transparent view of the supply chain, enabling companies to anticipate demand, optimize stock levels, and respond swiftly to supply chain disruptions. This comprehensive oversight has been pivotal in enhancing furniture companies' responsiveness to volatile market dynamics.

The cumulative impact of these digital technologies is profound. Production lines are not only more efficient but also more adaptable to changing consumer preferences. Design capabilities have expanded, allowing for a broader range of products to be offered. The supply chain has become more transparent and responsive, improving customer experience. As such, the digital age has not only reshaped the operations of the furniture industry but also set a new standard for what is possible within this traditional sector.

2. METHODS

The research is a literature review utilizing publications from ScienceDirect and Scopus databases. It focuses on the furniture industry: digital technologies like automation, robots, augmented reality, and IoT impact industry efficiency, sustainability, and profitability. The study will evaluate the contribution of these technologies to production processes, waste reduction, and profitability, alongside their role in sustainability and social responsibility. It will integrate case studies of furniture companies that have adopted these technologies, providing a practical perspective and, where possible, a comparative analysis of their implementation. The methodology will also suggest future research directions, particularly in emerging technologies and their long-term industry impact.

3. RESULT AND DISCUSSION

3.1. Furniture Industry

The furniture industry is a dynamic and highly competitive sector that has undergone significant changes in recent years. The emergence of global value chains and increased competition has resulted in the need for furniture manufacturers to adopt innovative practices to stay ahead. One approach to maintaining a competitive edge is continually improving product quality, which can be achieved by developing flexible and creative goods, collaborating with relevant stakeholders, and implementing advanced technologies such as automatic control systems and electrostatic powder coating. Despite the challenges, the furniture industry presents many opportunities for growth and innovation, making it an exciting and ever-evolving field.

3.1.1. Overview and Historical Context of the Furniture Industry

The furniture industry is diverse and dynamic, facing several problems and roadblocks in its operations. Caridi et al. (2012) found that the main challenge in aligning supply chain decisions is the level of complexity and creativity involved in the product. Specifically, they identified product modularity and innovativeness as essential factors contributing to this difficulty. Furthermore, Abu et al. (2019) identify technical knowledge, training, and financial resources as major hurdles when implementing lean manufacturing in furniture. As a result, to achieve sustainable growth, organizations in the furniture sector must address these problems by improving their technical competence, supply chain efficiency, and resource allocation.

In the furniture industry, global value chains are critical. According to Epede & Wang (2022), whereas African countries have remained at a comparative disadvantage, Asian countries of various economic levels have emerged as practical instances of sector upgrading. Even with their substantial competitive advantages, European and American countries face decreasing tendencies. Navas-Alemá (2011) also shows that upgrading is limited for developing-country enterprises that export through global value chains. As a result, the furniture industry must assess its position in global value chains and look for ways to improve its competitiveness in the worldwide market.

Technology integration in the furniture sector brings both benefits and obstacles. Firms confront considerable hurdles, such as the high cost of deploying automatic control technology and the necessity for specialized people to operate and maintain machinery. Likewise, optimizing pyrolysis parameters in Auger Reactor Pyrolysis can be difficult, and the qualities of the produced bio-oil may differ depending on the feedstock (Ahmed et al., 2020). As a result, businesses must assess the cost-benefit of integrating new technologies and devise methods to overcome the hurdles of technology adoption.

The furniture industry has been linked to some health risks, emphasizes the health risks associated with wood dust, and recognizes mechanical injuries resulting from unsafe working conditions and risky activities in the wood-bamboo furniture manufacturing business. Additionally, upholsterers, sanders, and sprayers are more likely to become ill than furniture workers (Vaajasaari et al., 2004). As a result, businesses must emphasize employee health and safety by implementing relevant measures such as ergonomic interventions and safe woodworking machinery.

3.1.2. Furniture Industry Structure

The furniture industry is complicated, with a supply chain that includes many stakeholders, such as suppliers, manufacturers, distributors, and retailers. Epede & Wang (2022) underline the necessity of integrating global value chains to promote industry competitiveness and upgrading. Furthermore, according to Abu et al. (2019), lean manufacturing can improve productivity, workplace organization, and space use. Azizi et al. (2016) recommend using a multi-criteria decision-making method to assess the sustainable growth of wooden furniture businesses since this method can identify and prioritize indices influencing the industry's sustainability.

The sector also faces worker health and safety issues. Woodworkers, for example, are at risk of nasal cancer. As a result, risk assessment and ergonomic evaluations are critical to treating pain-related and ergonomic concerns. To reduce the risk of musculoskeletal problems, Mirk (2005) suggests using safe woodworking machinery and ergonomic recommendations for the furniture manufacturing business.

Regarding innovation, according to Oliveira et al. (2016), information systems can reduce waste, optimize purchase and consumption, and increase profitability and sustainability. Furthermore, Jácome et al. (2021) propose a strategy that fosters innovation as a dynamic competence in the furniture sector, concentrating on business-led, collective innovation that prioritizes suppliers, consumers, competitors, and retailers.

Environmental sustainability is another critical part of the furniture industry (Farooq et al., 2022). Green value chain techniques can improve environmental performance by incorporating environmentally friendly practices into all value chain phases. Iritani et al. (2015) underline the importance of life cycle assessments in establishing more energy and resource-efficient manufacturing processes, which contribute to overall improvements in product environmental performance. Furthermore, Kremensas et al. (2021) emphasize the potential benefits of employing hemp shivs and corn-starch-based biocomposite boards, which offer more excellent water resistance and fire reactivity, to promote environmental sustainability.

Finally, the furniture sector has worker health and safety issues and environmental sustainability. Integrating global value chains and using lean manufacturing can boost competitiveness. The development of innovation as a dynamic competence in the industry can contribute to its progress. The industry should prioritize worker health and safety, develop sustainable practices, and employ life cycle evaluations.

3.2. Transforming The Furniture Industry

The furniture industry is in the midst of a digital transformation, with the increasing adoption of advanced technologies such as artificial intelligence, automation, and the Internet of Things. These innovations can revolutionize how furniture is designed, produced, and distributed, resulting in increased efficiency, improved sustainability, and enhanced customer experiences. The implementation of digital technology also offers the opportunity for greater customization, with consumers able to create bespoke designs and products tailored to their needs. However, the industry faces challenges such as high implementation costs, resistance to change, and the need for skilled labour to operate and maintain machines. Despite these obstacles, the transformative power of digital technology is evident, and the furniture industry that embraces these changes will likely enjoy a significant competitive advantage in the years ahead.

The integration of digital technology in the furniture industry has catalyzed a paradigm shift with profound economic implications. The advent of automated production lines and precision machinery has significantly reduced labour costs and minimized errors, leading to a leaner production model with enhanced profitability (Falheiro et al., 2022; Long et al., 2020). Digital inventory systems have streamlined supply chain management, preventing overproduction and excess stock and optimizing capital expenditure. Moreover, online sales platforms and digital marketing strategies have broadened market reach, allowing even small-scale manufacturers to access global markets, thus democratizing the competitive landscape.

However, the journey towards digital transformation has its challenges. Resistance to change is a significant hurdle, with a portion of the workforce often wary of new technologies perceived as threats to job security. Moreover, a gap in digital literacy can stymie the adoption of advanced technologies, necessitating investment in education and training. Companies must navigate these human factors with sensitivity and foresight, fostering an inclusive culture where technology is seen as an enabler rather than a disruptor.

Crystal Doors has digitalized its operations to remain competitive and achieve net-zero emissions. They established a network of sensors connecting their machines through the cloud to a dashboard, which has led to operational efficiencies and reduced emissions. Their digital transformation included workshops and workforce development to integrate emerging technologies and manage cultural change.

3.2.1. The Role of Digital Technology in the Furniture Industry

The furniture sector is undergoing substantial changes in the digital age, and integrating digital technologies has become critical. According to Carpano et al. (2006), international rivalry and a resource-based conception of the company drive changes in mature localized sectors. The sector must adapt to new business settings to stay competitive, and digital technology provides a means. However, (Abu et al., 2019) state that personnel-related concerns, a lack of implementation know-how, and employee resistance impede the implementation of lean practices in organizations. Adopting digital technology and its numerous capabilities can assist in overcoming these obstacles.

Digital technology is critical to the supply chain of the furniture industry. According to Caridi et al. (2012), supply chain decisions are affected by the complexity and creativity of products and can be customized to optimize performance. The industry can use digital technology to help it connect its supply chain with product characteristics and optimize performance. Digital technology can improve machine precision, efficiency, and accuracy, lowering costs connected with traditional manufacturing processes (Vidal et al., 2011).

Digital technology can also improve the furniture industry's sustainability practices. According to Azizi et al. (2016), high-priority sub-criteria include economic stability, developing industrial furniture clusters, adjusting furniture and wooden product importation tariffs, reducing volatile organic compounds, and marketing and union reinforcement creation of a competitive environment (Szczurek et al., 2021). Industry can use digital technology to help them meet these sub-criteria by decreasing waste, optimizing resource usage, and introducing sustainable manufacturing methods. Furthermore, digital technology may assist businesses in monitoring their environmental footprint and making necessary modifications (Linkosalmi et al., 2016).

The implementation of digital technology in the furniture industry needs to be improved. One issue is a need for more implementation expertise and employee resistance to change (Abu et al., 2019). Another area for improvement is the high expense of integrating digital technologies. The traditional market-pricing model understates financial losses. As a result, before making decisions, businesses must weigh the cost-benefit of integrating digital technologies.

Finally, the furniture sector must adopt digital technologies to compete in the digital age. Industry can use digital technology to optimize supply chains, increase sustainability practices, and minimize costs associated with traditional manufacturing methods. On the other hand, the industry must overcome hurdles relating to implementation know-how and employee resistance to change. Furthermore, businesses must weigh the cost-benefit of integrating digital technologies before making decisions. As the furniture industry evolves, digital technology will play an increasing role in altering the industry in the digital age.

3.3. Digital Transformation In The Furniture Industry

3.3.1. Challenges and Opportunities of the Furniture Industry

The furniture sector has a variety of difficulties and opportunities. Due to the industry's complexity, one crucial problem is matching supply chain decisions with product flexibility and innovativeness (Caridi et al., 2012). This problem has an impact on new product development as well as the implementation of modular furniture design. Another area for improvement is the high expense of integrating new technology, such as automatic control, and the requirement for skilled people to run and maintain the machinery. The high cost of technology deployment can negatively influence small and medium-sized firms' capacity to compete in the market.

The furniture sector faces environmental challenges as well. For example, Vicente et al. (2023) find that electrocoagulation treatment efficacy is insufficient to meet legal water discharge standards. The health risks associated with wood dust impair industrial personnel's health. The industry sector must adopt long-term policies and implement measures to ensure the safety of workers.

Furthermore, the furniture sector needs help in implementing new developments and technologies. According to Abu et al. (2019), technical knowledge, training, and financial resources are significant hurdles during the early stages of implementing lean manufacturing in the sector. Adopting new technology can impact competitiveness and limit the potential to develop (Han et al., 2009).

The references provided also emphasize prospects in the furniture sector. One possibility is using sustainable solutions, such as green value chain practices and Life Cycle Assessment (LCA) (Iritani et al., 2015). Adopting sustainable solutions can assist in addressing environmental issues while also increasing industry competitiveness. Another potential is using new technologies, such as Agile Product-Service Design with VR technology (Freitag et al., 2018). Using new technology can boost the industry's innovative skills and furniture producers' competitiveness.

The furniture industry's historical reliance on manual craftsmanship and skill has evolved dramatically with the advent of digital technology. Traditional methods were characterized by labour-intensive processes and long production cycles, often resulting in higher costs and limited scalability. In contrast, the industry's current state is defined by a synergy between skilled artisans and advanced technologies, leading to a renaissance in production and design.

A pivotal case study that exemplifies this evolution is the journey of 'Integral Surface Design (ISD)' a once-traditional manufacturer that embraced digital transformation. Integrating advanced CNC machinery into its production lines, Integral Surface Design increased its output by 50% while reducing material waste by 30%. Their adoption of 3D printing technology further allowed for rapid prototyping, enabling them to bring products to market in half the time previously required. This agility has been critical in maintaining its competitive edge in a market driven by fast-changing consumer preferences.

Another example is IKEA, a startup that disrupted the market by leveraging virtual reality (VR) to offer immersive design experiences to its customers (Kostecka & Kopczewska, 2023). Agile Product-Service Design with VR-technology: A use case in the furniture industry (Freitag et al., 2018). This technology allowed clients to visualize custom furniture pieces within their homes, leading to a 40% increase in customer satisfaction and a significant uptick in bespoke orders. IKEA has set a new standard for customer engagement in the digital age, showcasing the potential for technology to enhance the manufacturing process and the end-user experience.

These cases underscore a broader industry trend: companies that integrate digital technologies set benchmarks for efficiency, innovation, and customer engagement. As a result, they are redefining success in the furniture industry, proving that integrating digital tools is not merely an operational upgrade but a strategic imperative for growth and sustainability in the 21st century.

Finally, as emphasized in the referenced references, the furniture sector faces various difficulties and opportunities. Aligning supply chain decisions with the complexity and creativity of products, deploying new technologies, and addressing environmental and health risks are all challenges. Opportunities in the industry, on the other hand, include the adoption of sustainable practices and new technologies. The furniture industry must adopt innovative technologies and sustainable techniques to remain competitive and overcome the issues it confronts.

3.3.2. Case Studies of the Furniture Industry

The furniture business is undergoing a tremendous transition in the digital age, with digital technologies resulting in various benefits and issues. One significant benefit of digital technology in the furniture sector is better efficiency, workplace organization, and space use. According to Abu et al. (2019), technical expertise, training, and financial resources are all mentioned as hurdles during the early stages of implementation. Additionally, anticipating and preempting evolving environmental rules and customer expectations is essential in incorporating environmentally friendly activities into all value chain stages (Linkosalmi et al., 2016).

However, the furniture business faces various hurdles when it comes to using digital technology. According to Caridi et al. (2012), the critical obstacle is the difficulty in aligning supply chain decisions with product modularity and innovativeness due to the industry's complex character, which hinders supply chain performance alignment. Another area for improvement is the cost of deploying technology and the required qualified staff to run and maintain the devices. Ahmed et al. (2020) also address the difficulty of optimizing pyrolysis parameters, with the resulting bio-oil characteristics differing depending on the feedstock.

Although innovative technology and human integration are required to mitigate market risk for new product-service systems, Freitag et al. (2018) observe that this integration might be complex for enterprises. The challenges of enhancing process measurement instruments, process control, and quality assurance also exist. Contradictions between traditional manufacturing technology and new automation techniques can also be problematic. The use of integrated management and stakeholder management systems in small and medium-sized firms in the furniture industry impedes enhanced social and environmental implications of management decisions (Jaďuďová et al., 2015).

The advantages of digital technology within the furniture industry extend beyond operational efficiencies, profoundly enhancing product customization and customer experience (Falheiro et al., 2022; P. et al., 2022). Digital technologies, such as CAD/CAM software, have empowered customers to participate directly in the design process, tailoring furniture to their preferences and space requirements. This level of customization has transformed customer interactions from passive purchasing to active creation, resulting in a more engaged and satisfied customer base.

One illustrative example is 'Newport Furniture Parts,' which utilizes CNC machinery and CAD software to produce high-quality furniture parts. By adopting these technologies, they have ensured precision, reduced waste, and increased productivity. Their use of modern technology has helped them maintain their position as a leader in the wood component industry. Such innovations underscore the strategic value of customization in today's market, where differentiation is critical to capturing consumer attention and loyalty.

Despite these advantages, the furniture industry faces significant hurdles in implementing digital technologies. The challenge often lies in overcoming the inertia of established practices and the apprehension towards the perceived complexity of new systems. Successful change management strategies have been central to navigating these challenges. This global company, IKEA, uses materials from sustainable sources such as FSC-certified wood and recycled materials. They have implemented energy-efficient manufacturing processes and waste reduction initiatives and use renewable energy sources. They also use innovative designs such as modular furniture and have a product line made from recycled PET bottles and reclaimed wood.

Herman Miller uses sustainable materials such as recycled content and rapidly renewable resources. They design furniture for durability and longevity, incorporate eco-design principles, and have embraced modular design principles. Herman Miller has also integrated technology, such as the Live OS system, with their products.

West Elm uses source sustainable materials like FSC-certified wood and organic cotton and partners with suppliers who share their commitment to sustainability. West Elm has also implemented energy-efficient manufacturing processes and offers recycling programs for their products.

Blu Dot Uses eco-friendly materials such as FSC-certified wood and recycled content and focuses on producing durable furniture. They have adopted energy-efficient manufacturing processes, waste reduction initiatives, and use renewable energy sources. Blu Dot is also known for implementing computer-controlled cutting and advanced robotics.

Ekomia Specializes in sustainable furniture manufacturing using materials like FSC-certified wood, recycled materials, and natural fibres. Their designs focus on durability and longevity and support the circular economy with furniture rental and buy-back programs. Ekomia also uses intelligent manufacturing processes and has embraced 3D printing technology for efficient production.

These case studies exemplify how digital technologies can be harnessed to drive the furniture industry's growth, efficiency, and sustainability. The synthesis of these experiences within the industry shows that while digital technology brings considerable benefits in customization and customer engagement, its successful deployment hinges on thoughtful change management strategies. These strategies must prioritize human factors, ensuring that technology adoption is about the tools and the people who use them.

Finally, the furniture sector is undergoing a substantial shift in the digital age, with digital technology resulting in various benefits and obstacles. There are several benefits to adopting digital technology, including increased efficiency, improved workplace organization and space utilization, and enhanced environmental performance. However, the industry faces challenges such as high implementation costs, difficulty adapting supply chain decisions to product complexity, and the requirement for skilled labour to operate and maintain machines, which impede widespread adoption. New product-service systems require novel technology and personnel integration to mitigate market risk. Businesses must face these issues to benefit from implementing digital technology and prosper in the digital age.

In the digital age, the furniture sector is undergoing a revolution. Freitag et al. (2018) emphasize using virtual and augmented reality technology in the furniture sector for agile product-service design, allowing customers to sample their desired products before purchasing, improving their buying experience. Tsang et al. (2022) also discuss that using big data analytics in the furniture industry has led to intelligent product design frameworks that allow for greater flexibility and self-improvement mechanisms and optimize production processes, reducing manufacturing costs and improving efficiency.

Another example of digital transformation in the furniture business is using information systems to reduce the wastage of raw materials created during manufacturing (O. Oliveira et al., 2016). Furniture makers can discover places where waste can be eliminated by collecting and evaluating data on the manufacturing process, resulting in cost savings and enhanced sustainability (O. Oliveira et al., 2016). Furthermore, de Lima Mesquita et al. (2018) highlight the usage of eco-particleboards derived from alternative raw materials such as acai fruit fibres as a more sustainable alternative to regular particleboards in the construction and furniture industries.

Even with the advantages of digital transformation in the furniture sector, there are still hurdles. The rapid growth of microelectronics and advanced automation techniques may result in incompatibilities between traditional manufacturing technologies and automation techniques. Furthermore, the furniture sector must handle the issue of hazardous waste generated throughout the manufacturing process. According to Vaajasaari et al. (2004), excess paint leftovers formed during the spray-painting process contain dangerous substances that persist in the solid waste, and toxicity may leak from residues in contact with water at landfill sites. As a result, furniture makers must establish sustainable manufacturing techniques that limit waste and harm the environment.

Finally, digital change in the furniture sector enables better consumer experiences, cost reductions, and sustainability. Furniture makers are adopting virtual and augmented reality technology, big data analytics, and information systems to enhance production processes and eliminate waste. However, inconsistencies between traditional manufacturing technology, automation techniques, and hazardous waste generation must be addressed to achieve sustainable change.

3.4. Strategies For Maintaining Competitive Advantage

In the realm of modern furniture manufacturing, the integration of advanced technologies like Artificial Intelligence (AI), the Internet of Things (IoT), automation, 3D modelling, CNC machinery, and Enterprise Resource Planning (ERP) systems is not just a trend but a paradigm shift. AI is revolutionizing design processes through predictive analytics and customized design solutions, enhancing creativity and efficiency. IoT, with its network of interconnected devices, offers unparalleled monitoring and control over production processes, leading to significant improvements in operational efficiency. Automation, in its many forms, from robotic assembly lines to automated logistics, redefines furniture production's speed and precision.

Furthermore, 3D modelling has opened new horizons in furniture design, allowing for intricate and precise models that can be easily modified and visualized before production. CNC machinery complements this by turning these digital designs into reality with unmatched accuracy, drastically reducing the time and material waste traditionally associated with manufacturing. Lastly, ERP systems are the backbone of supply chain management, integrating various processes from inventory management to customer relations, ensuring a seamless flow of information and resources across the entire value chain.

Together, these technologies are streamlining production and design and reimagining the entire supply chain management, making it more responsive, efficient, and customer-centric. By exploring these technologies in greater depth, we can better understand their transformative impact on the furniture industry, paving the way for a future where innovation, efficiency, and sustainability are intrinsically linked.

The industry must adopt effective strategies to maintain a competitive edge in the highly competitive furniture industry. One approach is to develop and implement sustainable practices, such as using environmentally friendly materials and reducing waste. Another critical strategy is to prioritize innovation, constantly seeking new and creative designs that meet the evolving needs of consumers. Collaboration with relevant stakeholders, such as designers and suppliers, can also provide a competitive advantage by facilitating the exchange of ideas and expertise. Furthermore, leveraging digital technologies such as automation and artificial intelligence can improve production efficiency, reduce costs, and enhance product quality. Ultimately, a thriving furniture industry must be agile and adaptable, able to respond quickly to changes in the market and continually evolve its strategies to stay ahead of the competition.

3.4.1. Enhancing Product Quality

Because the furniture sector is characterized by fierce competition, businesses must constantly seek ways to maintain their competitive advantage. One strategy is to improve product quality, which is critical in satisfying client needs and maintaining a positive reputation (Robb & Xie, 2003).

Furthermore, innovation is critical in upgrading the value chain, aided by collaboration among essential stakeholders such as the government, industry actors, and individual enterprises (Epede & Wang, 2022). Global value chains have intensified competition in the wooden furniture industry. Collaborating with the right stakeholders can enable successful upgrading, as supported by their research and the findings of (Azizi et al., 2016), who developed a strategy for assessing the sector's long-term growth using multi-criteria decision-making. Their research identified high-priority sub-criteria such as increased economic stability, development of industrial furniture clusters, adjustment of furniture and wooden product import tariffs, reduction of volatile organic compounds, marketing, union reinforcement, and creation of a competitive environment.

In terms of technology, automatic control systems are critical for enhancing the efficiency and precision of machines in the furniture and construction industries. These technologies improve precision, efficiency, and accuracy, producing higher product quality. Additionally, Ayrilmi (2022) discovered that due to the development of low-temperature curing powder coatings and the fabrication of special-grade MDF panels, electrostatic powder coating had acquired broad application on wood-based panels. This technology improves product quality, making it essential for maintaining a competitive advantage.

The furniture industry is highly competitive, and maintaining a competitive edge requires continual improvements in product quality. The strategy will be achieved by developing flexible and innovative goods, collaborating with relevant stakeholders, implementing automatic control systems, and utilizing advanced technologies like electrostatic powder coating. By implementing these techniques, businesses in the furniture sector can separate themselves from competitors and retain a positive reputation among clients.

3.4.2. Enhancing Production Efficiency and Effectiveness

Improving manufacturing efficiency and effectiveness in the furniture sector is critical for maintaining a competitive advantage in the digital age. Using lean manufacturing, which focuses on waste elimination and process optimization, is one way to do this. According to Abu et al. (2019), lean businesses may need help with problems such as employee-related concerns, lack of implementation knowledge, and reluctance to change. However, the advantages of lean manufacturing are evident since it results in better resource use, shorter cycle times, and higher output.

Another technique for increasing production efficiency and effectiveness in the furniture and construction industries is to use automatic control systems. These methods improved machine precision, efficiency, and accuracy, allowing for more control and reduced human error in production operations. Similarly, intelligent product design frameworks based on big data analytics can improve manufacturing efficiency and effectiveness through increased flexibility and self-improvement mechanisms in product design evolution (Tsang et al., 2022).

Effective supply chain management improves performance and competitiveness. Caridi et al. (2012) discovered that product modularity and innovativeness influence supply chain decisions. Aligning supply chain choices with these product qualities might maximize performance. According to Epede & Wang (2022), expanding global value chains has impacted the furniture business by increasing competition. The participation of major stakeholders such as government, industry actors, and individual enterprises can result in successful value chain upgrading (Scott, 2006).

The furniture sector can use many innovations and technologies to reduce waste and promote sustainability. Eco-particleboard manufacture employing acai fruit fibres, for example, resulted in superior mechanical qualities and could be used as raw materials for medium-density homogeneous particleboards in the building and furniture industries (de Lima Mesquita et al., 2018). Using life cycle assessment (LCA), Iritani et al. (2015) identified two sustainable strategies: optimizing transportation systems using alternative raw materials and using 100% wood waste, which is more sustainable for medium-density particleboard manufacture. Figure 1 shows sustainable manufacturing practices using recycled plastic in furniture production. The benefits of using sustainable furniture practices include reducing waste and pollution, conserving natural resources, and promoting ethical production standards. The implementation of closed-loop production systems to reduce waste and the use of eco-friendly finishes or coatings that are free of harmful chemicals.

Enhancing occupational health and safety in the furniture sector can boost productivity and effectiveness. Ergonomic treatments, such as hand tool redesign, can considerably reduce risk factor exposure and enhance awareness of musculoskeletal problems and unsafe postures among small-scale furniture workers ((Jain et al., 2020); (Mirka, 2005). According to Ratnasingam et al. (2012), contract employees in the furniture business had a lower risk of occupational accidents and a more positive attitude toward safe working procedures.

Finally, the furniture business can preserve a competitive edge in the digital age by improving production efficiency and effectiveness. Lean manufacturing, autonomous control systems, intelligent product design frameworks, and effective supply chain management can optimize resource utilization, cut cycle times, and boost productivity. Furthermore, reducing waste, promoting sustainability, and improving employee health and safety can help the furniture industry's production efficiency and effectiveness.

3.4.3. Advancements in Marketing

In the digital age, the furniture business faces more competition and upheaval. Businesses must embrace creative techniques, such as marketing improvements. Azizi et al. (2016) proposed a multi-criteria decision-making strategy for assessing the long-term viability of the wooden furniture sector. As a high-priority sub-criteria, the study emphasizes the importance of economic stability, the construction of furniture manufacturing clusters, the elimination of volatile organic compounds, and the creation of a competitive environment. Businesses that prioritize these factors are more likely to get a competitive advantage.

Industry must focus on innovation and sustainability. Ng Thiruchelvam (2012) conducted a case study on Malaysia's Muar furniture cluster, highlighting the role of innovation in the industry's success. The industry must be creative and adaptable in product creation, production, and marketing approaches (Wu et al., 2023). Figure 2 shows an example of AR/VR technology used in the furniture industry: the IKEA Place app. This app allows users to use their smartphone camera to visualize how IKEA furniture would look in their homes. Using AR technology, the app can overlay furniture images onto the user's camera view, giving them an idea of how it would fit into their space.

Another example is the Wayfair app, which includes an AR feature called "View in Room." This feature allows customers to use their smartphone camera to place a 3D model of a piece of furniture into their room and see how it would look in real-time. It gives customers a better sense of the furniture's size and scale and helps reduce the risk of purchasing something that does not fit well in their space.

Furthermore, Jácome et al. (2021) suggested a methodology for establishing innovation as a dynamic competence for furniture sector organizations. The research finds organizational elements that promote the development of dynamic capabilities, thereby supporting businesses in sustaining a competitive advantage (Guimarães et al., 2016).

The industry must thoroughly know its market and client requirements to implement these strategies correctly. The green value chain activities in the furniture sector conclude that businesses must identify environmentally friendly methods in various value chain functions. Businesses prioritize meeting customers' demands while implementing sustainable practices. Additionally, (Carpano et al., 2006) emphasize the significance of changes in the mature localized sector due to international rivalry and the firm's resource-based orientation. Businesses that recognize and adapt to market developments are more likely to sustain their competitive advantage.

On the other hand, the industry must examine potential hurdles to implementing marketing enhancement initiatives. According to Abu et al. (2019), as implementation challenges, lean organizations encounter staff-related issues, a lack of implementation knowledge, and employee reluctance to change. These difficulties highlight the importance of good change management and staff engagement in successfully implementing marketing improvement plans.

The furniture industry must implement new strategies focused on sustainability, innovation, and client needs to preserve a competitive advantage in the digital age. Addressing possible roadblocks, such as employee resistance to change, is critical for successfully implementing these techniques. The industry may revolutionize the furniture sector in the digital age by emphasizing these criteria and successfully adopting marketing optimization tactics.

Figure 1. Examples of sustainable manufacturing practices in the furniture industry (credit: Pixabay). Some images from Pixabay have been merged and modified by adding additional labels and text.

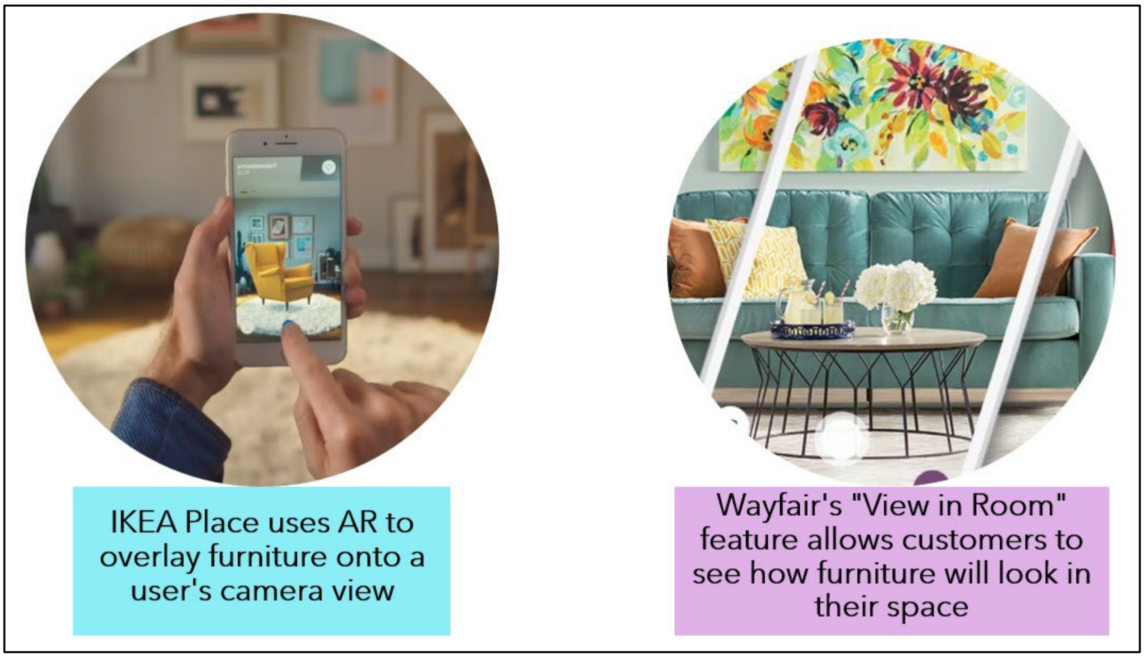

Figure 2. Examples of augmented reality (AR) and virtual reality (VR) technology are being used in the furniture industry (credit: IKEA and Wayfair)—images from IKEA and Wayfair are modified by adding additional labels and text.

4. CONCLUSION

The journey of the furniture industry into the digital age has been marked by a series of transformative changes driven by the adoption of digital technology. The analysis underscores the pivotal role of technologies such as CNC machinery, 3D modelling, and ERP systems in revolutionizing production, design, and supply chain management. These technologies have enhanced operational efficiencies and opened new avenues for product customization, elevating the customer experience to unprecedented levels.

The case studies of Integral Surface Design (ISD), IKEA, Newport Furniture Parts, Herman Miller, West Elm, Blu Dot, Ekomia, and others serve as testaments to the economic benefits and competitive advantages that digital technology can yield. However, the successful integration of these technologies is contingent upon overcoming challenges inherent in digital transformation. It requires robust change management strategies sensitive to workforce concerns and committed to fostering a culture of continuous learning and innovation.

As the furniture industry looks forward, it must not only embrace current digital trends but also remain vigilant to the evolving technological landscape. Continuous innovation and adaptation are not mere options but necessities for sustaining growth and relevance in an increasingly digital marketplace. The future of the furniture industry lies in its ability to leverage technology not just as a tool for efficiency but as a cornerstone for creating value, driving creativity, and delivering solutions that resonate with the dynamic needs of consumers.

The digital age is not a phase but a new reality for the furniture industry. Companies that understand and act upon the imperatives of digitalization will lead the way in setting standards for quality, sustainability, and customer satisfaction. Through this lens, the furniture industry can envisage and shape its future—a digital, innovative, and inclusive future.

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