

**FERRITE-BASED OXIDES:
PREPARATION, CHARACTERIZATION
AND CARBON DIOXIDE
ADSORPTION STUDY**

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by

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TABLE OF CONTENTS

ACKNOWLEDGEMENT	ii
TABLE OF CONTENTS.....	iii
LIST OF TABLES	x
LIST OF FIGURES	xiii
LIST OF SYMBOLS	xxii
LIST OF ABBREVIATIONS	xxiv
ABSTRAK	xxvi
ABSTRACT	xxix
CHAPTER 1 INTRODUCTION.....	1
1.1 Background	1
1.1.1 Climate change and CO ₂ emission	1
1.1.2 CO ₂ capture	2
1.2 Problem statement	4
1.3 Research objectives	7
1.4 Significance of study	7
1.5 Scope of study	9
1.6 Thesis layout	10
CHAPTER 2 LITERATURE REVIEW.....	11
2.1 Impact of industrialization on CO ₂ emission and climate change.....	11
2.2 Current materials for CO ₂ capture.....	12
2.3 Liquid adsorbents	13
2.3.1 Aqueous amino acids	13
2.3.2 Aqueous monoethanolamine (MEA)	14

2.3.3	Ionic liquids (ILs).....	15
2.3.4	Aqueous solution of hydroxides	16
2.4	Criteria for selecting solid CO ₂ capture materials.....	17
2.5	Solid adsorbents	23
2.5.1	Carbonaceous materials	24
2.5.2	Metal-organic frameworks (MOFs)	26
2.5.3	Zeolite adsorbent.....	27
2.5.4	Hydrotalcites (HTlcs).....	30
2.5.5	Metal oxides	32
2.6	Ferrite as CO ₂ solid adsorbent.....	35
2.7	Principle and mechanism of CO ₂ adsorption	40
2.8	Method for preparation of ferrite adsorbent.....	41
2.8.1	Solid state milling	42
2.8.2	Hydrothermal	43
2.8.3	Microemulsion	44
2.8.4	Sonochemistry.....	45
2.8.5	Sol-gel	46
2.9	Modification of metal oxides	53
2.9.1	Metal doping	53
2.9.2	Impregnation of metal oxides on supported material.....	57
2.9.3	Halloysite nanotubes (HNTs).....	60
2.9.4	Natural clay-based for gas adsorption application.....	61
CHAPTER 3	EXPERIMENTAL	65
3.1	Materials.....	65
3.2	Synthesis ferrite-based oxides	65

3.2.1	Preparation of NiFe_2O_4	66
3.2.2	Preparation of $\text{BaFe}_{12}\text{O}_{19}$	66
3.2.3	Preparation of $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$	66
3.3	Synthesis $\text{BaNi}_2\text{Fe}_{16-x}\text{Al}_x\text{O}_{27}$	67
3.4	Synthesis HNT/ $\text{BaNi}_2\text{Fe}_{16-x}\text{Al}_x\text{O}_{27}$	68
3.5	Characterizations	69
3.5.1	X-ray diffraction (XRD)	69
3.5.2	Fourier transform infrared spectroscopy (FTIR)	70
3.5.3	Scanning electron microscopy-energy dispersive X-ray spectroscopy (SEM-EDX)	71
3.5.4	Transmission electron microscopy (TEM)	72
3.5.5	X-ray photonelectron spectroscopy (XPS)	72
3.5.6	Thermogravimetric analyzer (TGA)	72
3.5.7	Nitrogen adsorption-desorption (NAD)	73
3.5.8	Basicity analysis via Hammett indicators and benzoic acid titration method	73
3.5.9	Temperature-programmed desorption (CO_2 -TPD) analysis	74
3.6	Experimental design in synthesis	75
3.6.1	Evaluation on the effect of molar ratio of citric acid to metal ions (CA:MI)	75
3.6.2	Evaluation on the effect of calcination temperature	76
3.6.3	Evaluation on the effect of calcination time	77
3.7	Impact of varying Al loading impregnated on HNT	77
3.7.1	Evaluation on the effect of different amount of Al loading in $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$	77
3.7.2	Evaluation on the effect of different amount of $\text{BaNi}_2\text{Fe}_{16-x}\text{Al}_x\text{O}_{27}$ ($x = 1.0$) on HNT	78

3.8	CO ₂ adsorption studies using adsorbents	78
3.8.1	Experimental setup.....	78
3.8.2	Effect of the carbonation temperature.....	79
3.8.3	Effect of the adsorbent loading	80
3.8.4	Effect of the gas flow rate	80
3.9	Reusability studies.....	80
3.10	Adsorption process	82
3.10.1	Kinetic adsorption models	82
3.10.2	Isotherm adsorption.....	83
3.10.3	Activation energy analysis	86
3.10.4	Adsorption process thermodynamics	86
3.11	Outline of experiment approach.....	87
 CHAPTER 4 OPTIMIZATION OF VARIOUS SYNTHESIS PARAMETERS, CHARACTERIZATIONS AND CARBON DIOXIDE ADSORPTION OF FERRITE-BASED OXIDES.. 88		
4.1	Overview	88
4.2	Optimization synthesis of ferrite-based oxides.....	89
4.2.1	Effect of the chelating agent molar ratio (citric acid to metal ions, CA:MI)	89
4.2.2	Effect of the calcination temperature	97
4.2.3	Effect of the calcination time	103
4.3	Characterization of ferrite-based oxides.....	111
4.3.1	Structural and crystallite analysis	111
4.3.2	Scanning electron microscopy-energy dispersive X-ray spectroscopy (SEM-EDX) analysis	116
4.3.3	Fourier transform infrared spectroscopy (FTIR) analysis.....	123
4.3.4	X-ray photoelectron spectroscopy (XPS) analysis.....	125

4.3.5	Nitrogen adsorption-desorption (NAD) analysis	132
4.3.6	Basicity analysis.....	136
4.4	Mechanism	138
4.4.1	Citric acid-mediated synthesis of ferrite-based oxides.....	138
4.5	CO ₂ adsorption study of ferrite-based oxides.....	141
4.5.1	Adsorption capacity	141
4.5.2	CO ₂ adsorption mechanism.....	144
4.6	Adsorption behaviour	145
4.6.1	Effect of the temperature.....	146
4.6.2	Effect of the adsorbent loading	147
4.6.3	Effect of the gas flow rate	148
4.6.4	Reusability studies	150
4.7	Adsorption process ferrite-based oxides	151
4.7.1	Kinetics models of adsorption.....	151
4.7.2	Adsorption isotherm analysis.....	154
4.7.3	Activation energy analysis	158
4.7.4	Adsorption thermodynamics	160
4.8	Comparative studies with previous works	162
4.9	Summary	168
CHAPTER 5 CHARACTERIZATIONS AND CARBON DIOXIDE ADSORPTION OF Al-DOPED BaNi₂Fe₁₆O₂₇ PREPARED VIA SOL-GEL METHOD		170
5.1	Overview	170
5.2	Characteristics of Al-doped BaNi ₂ Fe ₁₆ O ₂₇	171
5.2.1	X-ray diffraction (XRD) analysis	171
5.2.2	Fourier transform infrared spectroscopy (FTIR) analysis.....	177

5.2.3	Scanning electron microscopy-energy dispersive X-ray spectroscopy (SEM-EDX) analysis	179
5.2.4	Size distribution analysis	182
5.2.5	Nitrogen adsorption-desorption (NAD) analysis	183
5.2.6	Basicity analysis.....	186
5.2.7	Thermogravimetric analysis (TGA).....	187
5.3	CO ₂ adsorption study of BaNi ₂ Fe _{16-x} Al _x O ₂₇	189
5.3.1	Adsorption capacity	189
5.3.2	Reusability studies	194
5.4	Adsorption process.....	195
5.4.1	Kinetics models of adsorption.....	195
5.4.2	Adsorption isotherm analysis.....	198
5.4.3	Activation energy analysis	201
5.4.4	Adsorption thermodynamics	202
5.5	Proposed CO ₂ adsorption mechanism and schematic illustration.....	203
5.6	Summary	206
CHAPTER 6 PREPARATION AND CHARACTERIZATIONS OF IMPREGNATED HALLOYSITE NANOTUBES/BaNi₂Fe_{16-x}Al_xO₂₇ FOR ENHANCED CARBON DIOXIDE ADSORPTION		208
6.1	Overview	208
6.2	Appearances of HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇	209
6.3	Characteristics of HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇	210
6.3.1	X-ray diffraction (XRD) analysis	210
6.3.2	Fourier transform infrared spectroscopy (FTIR) analysis.....	212
6.3.3	Scanning electron microscopy-energy dispersive X-ray spectroscopy (SEM-EDX) analysis	215

6.3.4	Nitrogen adsorption-desorption (NAD) analysis	219
6.3.5	Thermogravimetric analysis (TGA).....	221
6.3.6	Temperature-programmed desorption (CO ₂ -TPD) analysis	223
6.4	CO ₂ adsorption study of HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇₋₁₂	225
6.4.1	Effect of the temperature.....	225
6.4.2	Effect of the adsorbent loading	227
6.4.3	Effect of the gas flow rate	148
6.4.4	Adsorption capacity	229
6.4.5	Comparative studies with previous works	231
6.4.6	Reusability studies	232
6.5	Adsorption process HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇₋₁₂	233
6.5.1	Kinetics models of adsorption.....	233
6.5.2	Adsorption isotherm analysis.....	236
6.5.3	Activation energy analysis	239
6.5.4	Adsorption thermodynamics	240
6.6	Schematic representation of adsorption	242
6.7	Summary	243
CHAPTER 7 CONCLUSION AND FUTURE RECOMMENDATIONS ...		245
7.1	Conclusion.....	245
7.2	Recommendations for future works	250
REFERENCES.....		252
LIST OF PUBLICATIONS AND PRESENTATIONS		

LIST OF TABLES

	Page
Table 1.1 Fossil fuel emission levels (IEA, 2024)	2
Table 2.1 Cost effectiveness and features of adsorbents for CO ₂ capture (Hambali <i>et al.</i> , 2014)	22
Table 2.2 Summary of the adsorbents and their performance in CO ₂ capture from the previous study.....	39
Table 2.3 Summary of synthesis methods and parameters for ferrite-based oxides using different method with different parameters	51
Table 2.4 Influences of metal dopants on CO ₂ adsorption activities	56
Table 2.5 Comparison of CO ₂ adsorption capacities of HNT-based adsorbents reported in the literature under different temperature	64
Table 3.1 Indicators for basicity measurement	74
Table 3.2 The parameters investigated and constant values for solvent ratio study	76
Table 3.3 The parameter investigated and constant values for the calcination temperature.....	77
Table 3.4 The parameter investigated and constant values for the calcination time.....	77
Table 3.5 Pseudo-first order (PFO) and pseudo-second order (PSO) kinetics models equation	83
Table 3.6 Langmuir, Freundlich and Temkin isotherm model parameters.....	86
Table 4.1 Summarizes the lattice parameters and crystallite size of ferrite-based oxides	114
Table 4.2 FTIR absorption bands and corresponding functional groups	125
Table 4.3 The S _{bet} , pore volume and amount of CO ₂ adsorbed at equilibrium of (a) NiFe ₂ O ₄ , (b) BaFe ₁₂ O ₁₉ and (c) BaNi ₂ Fe ₁₆ O ₂₇	133

Table 4.4	Basicity of ferrite-based oxides tested using Hammett indicators ..	137
Table 4.5	Pseudo-first order (PFO) and pseudo-second order (PSO) rate constant and relative error (%) by linear method for CO ₂ adsorption for BaNi ₂ Fe ₁₆ O ₂₇ at different temperatures.....	152
Table 4.6	Langmuir and Freundlich model parameters for BaNi ₂ Fe ₁₆ O ₂₇	155
Table 4.7	Thermodynamic parameters ΔH° , ΔS° , ΔG° for CO ₂ adsorption....	162
Table 4.8	Comparison ferrite-based oxides using different synthesis conditions in sol-gel method	165
Table 4.9	Comparison of CO ₂ capacity of ferrite-based oxides with previous studies.....	166
Table 5.1	Crystalline parameters of BaNi ₂ Fe _{16-x} Al _x O ₂₇ ($0.0 \leq x \leq 1.0$)	174
Table 5.2	Calculation of force constant from FTIR analysis for BaNi ₂ Fe _{16-x} Al _x O ₂₇ ($0.3 \leq x \leq 1.0$)	179
Table 5.3	BET surface area and pore volume of BaNi ₂ Fe _{16-x} Al _x O ₂₇ ($0.3 \leq x \leq 1.0$)	186
Table 5.4	Basicity of ferrite-based oxides and their doping tested using Hammett indicators	187
Table 5.5	Pseudo-first order (PFO) and pseudo-second order (PSO) rate constant and correlation coefficient for the BaNi ₂ Fe _{16-x} Al _x O ₂₇ ($x=1.0$) with various temperatures	196
Table 5.6	Langmuir and Freundlich model parameters for BaNi ₂ Fe _{16-x} Al _x O ₂₇ ($x=1.0$)	198
Table 5.7	Crystalline parameters of BaNi ₂ Fe _{16-x} Al _x O ₂₇ ($0.0 \leq x \leq 1.0$)	203
Table 6.1	CO ₂ -TPD data for the HNT/Al-BaNi ₂ Fe _{16-x} Al _x O ₂₇ in various loading	225
Table 6.2	Comparison of various adsorbents from reported literature for CO ₂ adsorption activity	232

Table 6.3	Pseudo-first order (PFO) and pseudo-second order (PSO) rate constants and correlation coefficient for the HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇₋₁₂ at 50 and 70 °C.....	235
Table 6.4	Langmuir, Freundlich and Temkin model parameters for HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇₋₁₂	237
Table 6.5	Thermodynamic parameters ΔH° , ΔS° and ΔG° for HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇₋₁₂	241

LIST OF FIGURES

	Page
Figure 2.1 CO ₂ capture reaction mechanism with aqueous amino acids (Custelcean <i>et al.</i> , 2019).....	14
Figure 2.2 The important properties and criteria for selecting CO ₂ capture materials	18
Figure 2.3 Number of publications on CO ₂ capture with various solid adsorbents since 2013, based on Scopus with keywords “CO ₂ adsorption” or “CO ₂ capture” (Dziejarski <i>et al.</i> , 2023).....	24
Figure 2.4 Tetrahedral arrangement of AlO ₄ found in zeolite structures (Khaleque <i>et al.</i> , 2020).....	28
Figure 2.5 The interaction in a linear orientation by an ion-dipole between metal ion and CO ₂	28
Figure 2.6 Schematic mechanism of CO ₂ adsorption in the zeolite Y structure (Zagho <i>et al.</i> , 2021).....	29
Figure 2.7 Metal oxides explore as materials for CO ₂ adsorption (Dziejarski <i>et al.</i> , 2023)	33
Figure 2.8 The modification strategies and research directions of ferrite– based oxides adsorbents	37
Figure 2.9 Illustration of the CO ₂ adsorption and desorption mechanism on the surface of a metal oxide	41
Figure 2.10 The sol-gel synthesis steps (Danks <i>et al.</i> , 2016)	48
Figure 2.11 Schematic illustration of the surface structure before and after metal doping, showing the interaction between CO ₂ molecules and doped metal oxide surfaces (Zhao <i>et al.</i> , 2024)	54
Figure 2.12 Proposed adsorption mechanism of CO ₂ and dope iron oxide (Chanapatttharapol <i>et al.</i> , 2017).....	59

Figure 2.13	Crystal structure of HNT is distinguished from kaolinite by the presence of a monolayer of water molecules in the HNT interlayer space (Fahimizadeh <i>et al.</i> , 2024)	60
Figure 3.1	Schematic representation of the experimental setup for CO ₂ adsorption analysis	79
Figure 3.2	Typical CO ₂ adsorption and desorption cycles from TGA profiles (Ojwang <i>et al.</i> , 2018)	81
Figure 3.3	Flow diagram of experimental work involved in the study	87
Figure 4.1	Physical appearances of (a) NiFe ₂ O ₄ (b) BaFe ₁₂ O ₁₉ and (c) BaNi ₂ Fe ₁₆ O ₂₇ with a molar ratio of CA:MI = 1.2:1	90
Figure 4.2	Schematic representation of the experimental setup for CO ₂ adsorption analysis	79
Figure 3.2	Typical CO ₂ adsorption and desorption cycles from TGA profiles (Ojwang <i>et al.</i> , 2018)	81
Figure 3.3	Flow diagram of experimental work involved in the study	87
Figure 4.1	Physical appearances of (a) NiFe ₂ O ₄ (b) BaFe ₁₂ O ₁₉ and (c) BaNi ₂ Fe ₁₆ O ₂₇ with a molar ratio of CA:MI = 1.2:1	90
Figure 4.2	X-ray diffraction pattern for NiFe ₂ O ₄ adsorbent with the different molar ratio CA:MI under 500 °C calcination temperature in 4 hours; (a) 1:1 (b) 1.2:1 (c) 2:1	91
Figure 4.3	X-ray diffraction pattern for BaFe ₁₂ O ₁₉ adsorbent with the different molar ratio CA:MI under 900 °C calcination temperature in 4 hours; (a) 1:1 (b) 1.2:1 (c) 2:1	94
Figure 4.4	X-ray diffraction pattern for BaNi ₂ Fe ₁₆ O ₂₇ adsorbent with the different molar ratio CA:MI under 950 °C calcination temperature in 4 hours; (a) 1:1 (b) 1.2:1 (c) 2:1	97
Figure 4.5	Color appearance of NiFe ₂ O ₄ samples at different calcination temperatures: (a) as-prepared NiFe ₂ O ₄ (b) calcined at 300 °C (c) calcined at 450 °C and (d) calcined at 500 °C. The gradual color	

	change indicates phase transformation and crystallinity development with increasing calcination temperature.....	98
Figure 4.6	X-ray diffraction pattern of synthesised (a) as-prepared (b) 300 °C (c) 450 °C and (d) 500 °C under constant (CA:MI) molar ratio (1.2:1) in 4 hours for NiFe_2O_4	99
Figure 4.7	Color appearance of $\text{BaFe}_{12}\text{O}_{19}$ samples at different calcination temperatures: (a) as-prepared $\text{BaFe}_{12}\text{O}_{19}$ (b) calcined at 650 °C (c) calcined at 850 °C and (d) calcined at 900 °C. The gradual color change indicates phase transformation and crystallinity development with increasing calcination temperature.....	100
Figure 4.8	X-ray diffraction pattern of synthesised (a) as-prepared (b) 650 °C (c) 850 °C and (d) 900 °C under constant (CA:MI) molar ratio (1.2:1) in 4 hours for $\text{BaFe}_{12}\text{O}_{19}$	101
Figure 4.9	Color appearance of $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$ samples at different calcination temperatures: (a) as-prepared $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$ (b) calcined at 750 °C (c) calcined at 900 °C and (d) calcined at 950 °C. The gradual color change indicates phase transformation and crystallinity development with increasing calcination temperature.....	102
Figure 4.10	X-ray diffraction pattern of synthesised (a) as-prepared (b) 750 °C (c) 900 °C and (d) 950 °C under constant (CA:MI) molar ratio (1.2:1) in 4 hours for $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$	103
Figure 4.11	Color observation of NiFe_2O_4 synthesized at different calcination durations (a) 3 hours showing a brownish color and (b) 4 hours with a slightly darker brown color indicating further phase development	104
Figure 4.12	X-ray diffraction pattern of synthesised NiFe_2O_4 with different calcination duration (a) 3 hours and (b) 4 hours at constant temperature (500 °C), molar ratio CA:MI (1.2:1).....	105
Figure 4.13	Color observation of $\text{BaFe}_{12}\text{O}_{19}$ synthesized at different calcination durations (a) 3 hours showing of brown-colored and (b)	

	4 hours with a slightly darker brown color indicating further phase development	106
Figure 4.14	X-ray diffraction pattern of synthesised $\text{BaFe}_{12}\text{O}_{19}$ with different calcination duration (a) 3 hours and (b) 4 hours at constant temperature (900 °C), molar ratio CA:MI (1.2:1).....	107
Figure 4.15	Color observation of $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$ synthesized at different calcination durations (a) 3 hours showing of brown-colored and (b) 4 hours with a slightly darker brown color indicating further phase development	108
Figure 4.16	X-ray diffraction pattern of synthesised $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$ with different calcination duration (a) 3 hours and (b) 4 hours at constant temperature (950 °C), molar ratio CA:MI (1.2:1).....	109
Figure 4.17	Flow chart illustrating the optimization steps of ferrite-based oxides synthesis parameters and their respective impacts on crystallinity development	110
Figure 4.18	Unit cell of NiFe_2O_4 inverse spinel	111
Figure 4.19	Unit cell of $\text{BaFe}_{12}\text{O}_{19}$ (Moitra <i>et al.</i> , 2014)	112
Figure 4.20	Unit cell of $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$ (Morch <i>et al.</i> , 2019).....	113
Figure 4.21	(a) SEM micrographs in magnification 35 000x (b) particle size distribution histogram of NiFe_2O_4	116
Figure 4.22	(a) SEM micrographs in magnification 30 000x and (b) particle size distribution histogram of $\text{BaFe}_{12}\text{O}_{19}$	118
Figure 4.23	(a) SEM micrographs in magnification 30 000x (b) particle size distribution histogram of $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$	119
Figure 4.24	EDX spectra and the inset of analysis data of (a) NiFe_2O_4 , (b) $\text{BaFe}_{12}\text{O}_{19}$ and (c) $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$	121
Figure 4.25	Schematic illustration of the CO_2 adsorption reaction on $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$ correlation between crystallographic features (XRD) and surface morphology (SEM)	123

Figure 4.26	FTIR spectra of (a) NiFe_2O_4 , (b) $\text{BaFe}_{12}\text{O}_{19}$ and (c) $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$ adsorbent	125
Figure 4.27	Deconvolution of the XPS spectra of (a) Ni 2p _{1/2} , (b) Ni 2p _{3/2} , (c) Fe 2p _{1/2} , (d) Fe 2p _{3/2} and (e) O1s of synthesised NiFe_2O_4 under optimum conditions.....	128
Figure 4.28	Deconvolution of the XPS spectra of (a) Ba 3d _{3/2} , (b) Ba 3d _{5/2} , (c) Fe 2p _{1/2} , (d) Fe 2p _{3/2} , (e) Ni 2p _{1/2} , (f) Ni 2p _{3/2} and (g) O1s of synthesised $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$ under optimum conditions	130
Figure 4.29	Deconvolution of the XPS spectra of (a) Ba 3d _{3/2} , (b) Ba 3d _{5/2} , (c) Fe 2p _{1/2} , (d) Fe 2p _{3/2} , (e) Ni 2p _{1/2} , (f) Ni 2p _{3/2} and (g) O1s of synthesised $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$ under optimum conditions	132
Figure 4.30	Nitrogen adsorption-desorption isotherm plot and pore size distributions (inset) of (a) NiFe_2O_4 (b) $\text{BaFe}_{12}\text{O}_{19}$ and (c) $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$	135
Figure 4.31	The correlation of pore volume CO_2 uptake (Singh <i>et al.</i> , 2023)	136
Figure 4.32	Color change of indicators for ferrite-based oxides: BTB (orange to blue) and PHP (colorless to pink)	137
Figure 4.33	(a) The structural formula of citric acid. (b) Three-stages dissociation process of citric acid. (c) The chelating agent formed between citric acid and metal-ions (Ni chelation with 2-carboxyl group)	139
Figure 4.34	Esterification reaction between citric acid chelate and ethanol in modified sol-gel method	141
Figure 4.35	Esterification reaction between citric acid chelate and ethanol in modified sol-gel method	142
Figure 4.36	Graph of (a) q_e (mg g^{-1}) against BET surface area ($\text{m}^2 \text{g}^{-1}$) and (b) adsorption capacity (mg g^{-1}) against time (minutes) for NiFe_2O_4 , $\text{BaFe}_{12}\text{O}_{19}$ and $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$ at 30 °C	143
Figure 4.37	The effect of temperature on CO_2 adsorption for $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$	147

Figure 4.38	The effect of adsorbent loading on CO ₂ adsorption for BaNi ₂ Fe ₁₆ O ₂₇	148
Figure 4.39	The effect of flow rate on CO ₂ adsorption BaNi ₂ Fe ₁₆ O ₂₇	149
Figure 4.40	Reusability CO ₂ capture at 30 °C using BaNi ₂ Fe ₁₆ O ₂₇ by TGA.....	151
Figure 4.41	Kinetic plot (a) PFO and (b) PSO kinetic model of BaNi ₂ Fe ₁₆ O ₂₇ ..	153
Figure 4.42	Langmuir isotherm models for CO ₂ adsorption isotherm at 30 °C using BaNi ₂ Fe ₁₆ O ₂₇	154
Figure 4.43	Freundlich isotherm models for CO ₂ adsorption isotherm at 30 °C using BaNi ₂ Fe ₁₆ O ₂₇	156
Figure 4.44	Plot ln k ₂ against $\frac{1}{T}$ for CO ₂ adsorption onto BaNi ₂ Fe ₁₆ O ₂₇	159
Figure 4.45	Plot of ln k _L against $\frac{1}{T}$ for thermodynamic parameters for the CO ₂ adsorption on BaNi ₂ Fe ₁₆ O ₂₇	161
Figure 5.1	Physical appearances of (a) undoped BaNi ₂ Fe ₁₆ O ₂₇ (b) BaNi ₂ Fe _{16-x} Al _x O ₂₇ (x=0.3), (c) BaNi ₂ Fe _{16-x} Al _x O ₂₇ (x=0.5), (d) BaNi ₂ Fe _{16-x} Al _x O ₂₇ (x=1.0)	171
Figure 5.2	XRD patterns of undoped and Al–doped BaNi ₂ Fe ₁₆ O ₂₇ adsorbent: (a) x= 0 (b) x= 0.3 (c) x= 0.5 and (d) x=1.0. The insets show XRD pattern of the showing the position of 2θ at (116) diffraction	173
Figure 5.3	FTIR spectra of (a) BaNi ₂ Fe _{16-x} Al _x O ₂₇ (x= 0.3) (b) BaNi ₂ Fe _{16-x} Al _x O ₂₇ (x= 0.5) and (c) BaNi ₂ Fe _{16-x} Al _x O ₂₇ (x=1.0) in 400–4400 cm ⁻¹ and the enlarged peaks of the 400–1400 cm ⁻¹ region.....	178
Figure 5.4	SEM micrographs of BaNi ₂ Fe _{16-x} Al _x O ₂₇ (0.3 ≤ x ≤ 1.0) in magnification 30 000x: (a) x= 0.3, (b) x= 0.5 and (c) x= 1.0	180
Figure 5.5	EDX spectra and the inset of analysis data of BaNi ₂ Fe _{16-x} Al _x O ₂₇ (0.3 ≤ x ≤ 1.0), (a) x= 0.3, (b) x= 0.5 and (c) x= 1.0	182
Figure 5.6	Particle size distribution histogram of BaNi ₂ Fe _{16-x} Al _x O ₂₇ (a) x= 0.3, (b) x= 0.5 and (c) x= 1.0.....	183

Figure 5.7	Nitrogen adsorption-desorption isotherm and pore size distributions (inset) of $\text{BaNi}_2\text{Fe}_{16-x}\text{Al}_x\text{O}_{27}$ ($0.3 \leq x \leq 1.0$) (a) $x=0.3$, (b) $x=0.5$ and (c) $x=1.0$	185
Figure 5.8	Color change of indicators for (a) undoped $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$: BTB (orange to blue) and PHP (colorless to pink) (b) Al-doped $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$: BTB (orange to blue), PHP (colorless to pink) and 2,4 DN (green to yellow)	187
Figure 5.9	(a)TGA and (b) DTG curves of undoped and Al-doped $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$ with varies x composition ($0.3 \leq x \leq 1.0$)	188
Figure 5.10	FTIR spectra of (a) $\text{BaNi}_2\text{Fe}_{16-x}\text{Al}_x\text{O}_{27}$ ($x=0.3$) (b) $\text{BaNi}_2\text{Fe}_{16-x}\text{Al}_x\text{O}_{27}$ ($x=0.5$) and (c) $\text{BaNi}_2\text{Fe}_{16-x}\text{Al}_x\text{O}_{27}$ ($x=1.0$) in $400\text{--}4400\text{ cm}^{-1}$ and the enlarged peaks of the $400\text{--}1400\text{ cm}^{-1}$ region.....	189
Figure 5.11	SEM micrographs of $\text{BaNi}_2\text{Fe}_{16-x}\text{Al}_x\text{O}_{27}$ ($0.3 \leq x \leq 1.0$) in magnification 30 000x: (a) $x=0.3$, (b) $x=0.5$ and (c) $x=1.0$	191
Figure 5.12	EDX spectra and the inset of analysis data of $\text{BaNi}_2\text{Fe}_{16-x}\text{Al}_x\text{O}_{27}$ ($0.3 \leq x \leq 1.0$), (a) $x=0.3$, (b) $x=0.5$ and (c) $x=1.0$	193
Figure 5.13	Particle size distribution histogram of $\text{BaNi}_2\text{Fe}_{16-x}\text{Al}_x\text{O}_{27}$ (a) $x=0.3$, (b) $x=0.5$ and (c) $x=1.0$	195
Figure 5.14	Nitrogen adsorption-desorption isotherm and pore size distributions (inset) of $\text{BaNi}_2\text{Fe}_{16-x}\text{Al}_x\text{O}_{27}$ ($0.3 \leq x \leq 1.0$) (a) $x=0.3$, (b) $x=0.5$ and (c) $x=1.0$	196
Figure 5.15	Color change of indicators for (a) undoped $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$: BTB (orange to blue) and PHP (colorless to pink) (b) Al-doped $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$: BTB (orange to blue), PHP (colorless to pink) and 2,4 DN (green to yellow)	200
Figure 5.16	$\ln k_2$ against $1/T$ for CO_2 adsorption into $\text{BaNi}_2\text{Fe}_{16-x}\text{Al}_x\text{O}_{27}$ ($x=1.0$)	202
Figure 5.17	Van't Hoff plot for $\text{BaNi}_2\text{Fe}_{16-x}\text{Al}_x\text{O}_{27}$ ($x=1.0$) at various temperature.....	202

Figure 5.18	Schematic representation of (a) the adsorption–desorption process, and (b) monolayer adsorption of CO ₂ molecules onto the adsorbent surface. (Gupta <i>et al.</i> , 2021).....	206
Figure 6.1	Illustration of the development process for HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇	209
Figure 6.2	Physical appearance of (a) HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇ –4, (b) HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇ –8 and (c) HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇ –12	210
Figure 6.3	XRD patterns of HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇ adsorbent in various compositions. The XRD patterns of HNT and Al–BaNi ₂ Fe ₁₆ O ₂₇ are also shown in this figure	211
Figure 6.4	FTIR spectra of HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇ adsorbent in various composition. The XRD patterns of HNT and Al–BaNi ₂ Fe ₁₆ O ₂₇ are also shown in the figure	215
Figure 6.5	SEM images of (a) raw HNTs, (b) BaNi ₂ Fe _{16-x} Al _x O ₂₇ ($x= 1.0$), (c) HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇ –4 (1 μ m), (d) HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇ –4 (500 nm), (e) HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇ –8 (1 μ m), (f) HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇ –12, (g) TEM images of HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇ –12 (500 nm).....	218
Figure 6.6	EDX elemental analysis of (a) raw HNT and (b) HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇ –12.....	219
Figure 6.7	Nitrogen adsorption-desorption isotherms and pore size distribution (inset) of (a) HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇ –4, (b) HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇ –8 and (c) HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇ –12	220
Figure 6.8	(a) TGA and (b) DTG curves of HNT and HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇ with various loading.....	223
Figure 6.9	CO ₂ -TPD profiles of the HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇ in various loading.....	224
Figure 6.10	CO ₂ adsorption profiles of HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇ –12 adsorbent recorded as a function of time and temperature. (Adsorption conditions of HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇ –12: adsorbent loading = 3 mg, gas flow rate = 10 mL min ⁻¹)	227

Figure 6.11	Effect of the HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇₋₁₂ loading on the CO ₂ adsorption capacity (Adsorption conditions of HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇₋₁₂ : temperature = 50 °C, gas flow rate = 10 mL min ⁻¹)	228
Figure 6.12	Effect of the CO ₂ flow rate on the CO ₂ adsorption capacity (Adsorption conditions of HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇₋₁₂ : temperature = 50 °C, adsorbent loading = 3 mg)	229
Figure 6.13	CO ₂ adsorption of (a) HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇₋₄ , (b) HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇₋₈ and (c) HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇₋₁₂	230
Figure 6.14	The recyclability of HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇₋₁₂ adsorbent at optimum conditions.....	233
Figure 6.15	Kinetic plot (a) PFO model and (b) PSO kinetic model of HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇₋₁₂ at 50 and 70 °C	234
Figure 6.16	(a) Langmuir (b) Freundlich and (c) Temkin isotherm models for CO ₂ adsorption at 50 °C using HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇₋₁₂	238
Figure 6.17	ln k ₂ against 1/T for CO ₂ adsorption into HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇₋₁₂	240
Figure 6.18	Van't Hoff plot for HNT/BaNi ₂ Fe _{16-x} Al _x O ₂₇₋₁₂ at various temperature.....	241
Figure 6.19	Schematic diagram of (a) surface complexation of charged surface of HNT through chemisorption and (b) multilayer CO ₂ adsorption (Li <i>et al.</i> , 2019).....	242

LIST OF SYMBOLS

%	Percentage
±	Plus-minus
°	Degree
Al	Aluminium
°C	Degree Celsius
CO ₂	Carbon dioxide
Fe	Ferrite
g	Gram
h	Hour
K	Kelvin
k ₁	Kinetic rate constant for pseudo-first order
k ₂	Kinetic rate constant for pseudo-second order
m	Meter
mg	Milligram
min	Minute
mL	Milliliter
mmol	Millimole
mol %	Mol percent
N ₂	Nitrogen
nm	Nanometer
ppm	Parts per million
R ²	Correlation coefficient
s	Solid
S _{bet}	BET specific surface area
vol %	Volume percent

wt %	Weight percent
θ	Theta
λ	Wavelength

LIST OF ABBREVIATIONS

AC	Activated carbon
AMOST	Aqueous miscible organic solvent treatment
AP	Aminopropyltriethoxysilane
BECCS	Bioenergy with carbon capture and storage
BET	Brunauer-Emmett-Teller
BJH	Barrett-Joyner-Halenda
CA	Citric acid
CCS	CO ₂ capture and storage
CCU	Carbon capture and utilization
CCUS	Carbon capture, utilization and storage
CTAB	Cetyl- <i>N,N,N</i> -trimethylammonium bromide
CTAC	Cetyltrimethylammonium chloride
DAC	Direct air capture
DETA	Diethylenetriamine
DTG	Derivative thermogravimetry
EIA	Energy Administration
FTIR	Fourier Transform Infrared
FWHM	Full width at half maximum
GHG	Greenhouse gas
HNTs	Halloysite nanotubes
HTlc	Hydrotalcite
IL	Ionic liquid
IL-CP	Ionic liquid-conjugated polymer
IPCC	Panel on Climate Change
IUPAC	International Union of Pure and Applied Chemistry
JCPDS	Joint Committee on Powder and Applied Chemistry
LDH	Layered double hydroxides
LTA	Linde-Type A
MEA	Monoethanolamine
MI	Metal ions
MOFs	Metal-organic frameworks

NAD	Nitrogen adsorption-desorption
NMR	Nuclear magnetic resonance
PAA	Polyacrylic acid
PAN	Polyacrylonitrile
PEI	Polyethyleneimine
SEM-EDX	Scanning electron microscopy-energy dispersive X-ray spectroscopy
STP	Standard temperature and pressure
TGA	Thermogravimetric analysis
WMO	World meteorological organization
XPS	X-ray photoelectron spectroscopy
XRD	X-ray diffraction

OKSIDA BERASASKAN FERIT: PENYEDIAAN, PENCIRIAN DAN KAJIAN PENJERAPAN KARBON DIOKSIDA

ABSTRAK

Sebagai tindak balas terhadap permintaan yang semakin meningkat bagi teknologi penangkapan karbon yang berkesan, kajian ini menyelidik sintesis dan pencirian bahan penjerapan pepejal berasaskan ferit disediakan dengan menggunakan kaedah mudah sol-gel. Objektif utama adalah untuk meningkatkan kapasiti penjerapan, kebolehgunaan semula dan sifat struktur bahan penjerap. Selain itu, oksida berasaskan ferit ternar dan kuaterner telah melihat pejelajahan yang terhad dalam bidang penangkapan karbon yang sebahagian besarnya disebabkan oleh banyaknya kajian yang memfokuskan kepada oksida logam tunggal yang ringkas. Sistem pelbagai-logam yang kompleks ini menawarkan potensi untuk sifat penjerapan CO₂ yang lebih baik tetapi masih kurang dimanfaatkan. Dalam kajian ini, ferit spinel songsang bersama dengan bahan penjerap heksaferit jenis M dan W telah berjaya disintesis menggunakan kaedah kos rendah, mudah dan berkesan. Kapasiti penjerapan CO₂ oleh bahan penjerap ini dinilai melalui analisis termogravimetri. Oksida berasaskan ferit telah disintesis di bawah keadaan terbaik dengan suhu tindak balas 80 °C, nisbah optimum asid sitrik kepada ion logam (CA:MI) 1.2:1, masa tindak balas 30 minit dan masa pengkalsinan 4 jam. NiFe₂O₄, BaFe₁₂O₁₉ dan BaNi₂Fe₁₆O₂₇ masing-masing menunjukkan kapasiti penjerapan CO₂ sebanyak 11.31 mg g⁻¹, 17.33 mg g⁻¹, and 20.43 mg g⁻¹. BaNi₂Fe₁₆O₂₇ yang terdop dengan Al menunjukkan sifat yang dipertingkatkan. Ini menunjukkan prestasi penjerapan yang lebih baik berbanding bahan penjerap yang tidak terdop. Di bawah keadaan penjerapan optimum (3 mg bahan penjerap, kadar aliran 10 mL min⁻¹), BaNi₂Fe₁₆O₂₇ yang terdop dengan Al memaparkan

kapasiti penjerapan sebanyak 40.66 mg g^{-1} berbanding 20.46 mg g^{-1} yang dicapai oleh $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$ tanpa dop pada suhu 30°C . Pendopan meningkatkan luas permukaan dan isipadu liang, seperti yang disahkan melalui analisi BET yang menunjukkan peningkatan luas permukaan spesifik daripada 57.230 to $78.704 \text{ m}^2 \text{ g}^{-1}$ dan isipadu liang daripada 0.20141 kepada $0.42930 \text{ cm}^3 \text{ g}^{-1}$, sekaligus menyediakan permukaan yang lebih besar dan lebih mudah diakses untuk molekul CO_2 berinteraksi. Pendopan Al ke dalam $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$ membawa kepada peningkatan bilangan tapak asas aktif, yang menguatkan interaksi antara bahan penjerap dan molekul CO_2 . Bahan penjerap terdop Al menunjukkan kebolehgunaannya semula yang baik dengan mengekalkan aktiviti penjerapan yang tinggi sepanjang lima kitaran., serupa dengan prestasi bahan penjerap yang tanpa dop. Walaupun lima kitaran menunjukkan kebolehlaksanaan dan kecekapan regenerasi yang baik bagi kedua-dua $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$ yang didop and tidak didop, bahan penjerap yang diimpregnasi HNT telah meningkatkan prestasi penjerapan semula yang lebih baik. Oleh itu, $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$ yang didop dengan Al kemudiannya diimpregnasi ke dalam HNT untuk meningkatkan keupayaan penjerapannya dan kestabilan sepanjang kitaran yang berpanjangan. Bahan penjerap komposit HNT/ $\text{BaNi}_2\text{Fe}_{16-x}\text{Al}_x\text{O}_{27}$ menunjukkan prestasi penjerapan CO_2 yang lebih tinggi dengan kapasiti sebanyak 58.61 mg g^{-1} pada 30°C dan 70.17 mg g^{-1} pada 50°C berbanding dengan kedua dua varian $\text{BaNi}_2\text{Fe}_{16}\text{O}_{27}$ yang tanpa dop dan terdop. Prestasi penjerapan CO_2 tertinggi dicapai dengan menggunakan $12 \text{ wt } \%$ HNT/ $\text{BaNi}_2\text{Fe}_{16-x}\text{Al}_x\text{O}_{27}$. Penjerapan yang unggul oleh HNT/ $\text{BaNi}_2\text{Fe}_{16-x}\text{Al}_x\text{O}_{27}$ adalah disebabkan oleh luas permukaan yang lebih besar ($90.53 \text{ m}^2 \text{ g}^{-1}$), dan isipadu liang ($0.4229 \text{ cm}^3 \text{ g}^{-1}$) berbanding varian tidak didop dan didop, serta peningkatan ketersediaan tapak aktif berasas. Tambahan pula, kebesan HNT/ $\text{BaNi}_2\text{Fe}_{16-x}\text{Al}_x\text{O}_{27}$ adalah jauh lebih tinggi pada $2.770 \text{ mmol g}^{-1}$, berbanding $0.843 \text{ mmol g}^{-1}$ bagi yang tidak didop dan 1.412

mmol g⁻¹ bagi BaNi₂Fe₁₆O₂₇ yang didop, yang turut menyumbang kepada prestasi penjerapan CO₂ yang lebih unggul. Penjerapan oleh semua bahan penjerap mengikut model kinetik tertib pseudo-kedua. Tambahan lagi, bahan penjerap komposit HNT/BaNi₂Fe_{16-x}Al_xO₂₇ menunjukkan kebolegunaan semula yang lebih tinggi dan mengekalkan kecekapan lebih daripada 95 % selepas lima kitaran. Semua bahan penjerap oksida berasaskan ferit menunjukkan keupayaan untuk penjerapan CO₂, menawarkan potensi besar dalam pemulihan alam sekitar bagi mengurangkan pelepasan gas rumah hijau dan menangani perubahan iklim.

FERRITE–BASED OXIDES: PREPARATION, CHARACTERIZATION AND CARBON DIOXIDE ADSORPTION STUDY

ABSTRACT

In response to the growing demand for effective carbon capture technologies, this study investigates the synthesis and characterization of ferrite–based oxides solid adsorbents prepared using a facile sol-gel method. The primary aim is to enhance the adsorption capacity, reusability and structural properties of the adsorbent. Besides, ternary and quaternary ferrite–based oxides have seen limited exploration in the field of carbon capture, largely due to the prevalence of studies focusing on simpler single metal oxides. These complex multi-metal systems offer the potential for enhanced CO₂ adsorption properties yet remain underutilized. In this study, inverse spinel ferrite along with M-type and W-type hexaferrite adsorbents, were successfully synthesized using low-cost, facile and efficient method. The CO₂ adsorption capacity of the adsorbent was evaluated through thermogravimetric analysis. The ferrite–based oxides were synthesized under best conditions with a reaction temperature of 80 °C, the optimal citric acid to metal ion (CA:MI) of 1.2:1, a reaction time of 30 minutes and a calcination time of 4 hours. NiFe₂O₄, BaFe₁₂O₁₉ and BaNi₂Fe₁₆O₂₇ displayed CO₂ adsorption capacities of 11.31 mg g⁻¹, 17.33 mg g⁻¹, and 20.43 mg g⁻¹, respectively. The Al–doped BaNi₂Fe₁₆O₂₇ exhibited enhanced properties. It showed superior adsorption performance compared to the undoped adsorbent. Under optimum adsorption conditions, (3 mg adsorbents, 10 mL min⁻¹ of flow rate), the Al–doped BaNi₂Fe₁₆O₂₇ displayed 40.66 mg g⁻¹ of adsorption capacity at 30 °C. Al-doping increases the surface area and pore volume, as confirmed by BET analysis showing an increase from 57.230 to 78.704 m² g⁻¹ and pore volume from 0.20141 to 0.42930 cm³

g⁻¹ providing a larger and more accessible surface for CO₂ adsorption. The doping of Al into the BaNi₂Fe₁₆O₂₇ leads to an increased number of active basic sites, which strengthens the interaction between the adsorbent and CO₂ molecules. The Al-doped adsorbent showed better reusability, maintaining high adsorption activity over five cycles, similar to the performance of the undoped adsorbent. Although five cycles demonstrate good viability and regeneration efficiency for both doped and undoped BaNi₂Fe₁₆O₂₇, impregnating the adsorbent with HNTs significantly enhanced its long-term performance. Therefore, the Al-doped BaNi₂Fe₁₆O₂₇ was further impregnated into HNTs to improve its adsorption capacity. The HNT/BaNi₂Fe_{16-x}Al_xO₂₇ composite adsorbent demonstrated higher CO₂ adsorption performance achieving a capacity of 58.61 mg g⁻¹ at 30 °C and 70.17 mg g⁻¹ at 50 °C compared to both the undoped and doping variants of BaNi₂Fe₁₆O₂₇. The highest CO₂ adsorption performance was achieved by using 12 wt % of BaNi₂Fe_{16-x}Al_xO₂₇ loading. The superior adsorption of HNT/BaNi₂Fe_{16-x}Al_xO₂₇ is attributed to its significantly higher surface area (90.53 m² g⁻¹) and pore volume (0.4229 cm³ g⁻¹) compared to the undoped and doped variants along with enhanced availability of basic active sites. In addition, the basicity of HNT/BaNi₂Fe_{16-x}Al_xO₂₇ is significantly higher at 2.770 mmol g⁻¹, compared to 0.843 mmol g⁻¹ for undoped and 1.412 mmol g⁻¹ for the doped BaNi₂Fe₁₆O₂₇ which further contributing to its superior CO₂ capture performance. The adsorption by all adsorbents followed the pseudo-second order kinetic model. Furthermore, HNT/BaNi₂Fe_{16-x}Al_xO₂₇ composite adsorbent exhibited greater reusability and maintain over 95 % efficiency after five cycles. All ferrite-based oxide adsorbents demonstrated capability for CO₂ adsorption, serving as a great potential in environmental remediation for reducing greenhouse gas emissions and combating climate change.

CHAPTER 1

INTRODUCTION

1.1 Background

1.1.1 Climate change and CO₂ emission

Global warming has attracted the attention of many researchers and environmental scientists. It is mainly due to the rapid increase in population and energy consumption worldwide. High magnitudes of greenhouse gases released into the air has contributed to climate disasters. According to the Energy Administration (EIA), energy consumption is expected to increase by 57 % in 2030 (Santamouris and Vasilakopoulou, 2021). The emission of greenhouse gases contributes to most environmental problems and CO₂ is the major greenhouse gas that contributes to global warming (Kabir *et al.*, 2023; Filonchyk *et al.*, 2024). In addition, approximately 60 % of global warming effects are attributed to CO₂ emissions (WMO, 2023).

In the past, the total amount of CO₂ was relatively maintained at 280 ± 10 ppm and the atmospheric sink was considered large enough to accommodate any additional CO₂. This was until the industrial revolution. The amount of CO₂ has risen by more than a third since the industrial revolution. In the year 2000, the amount of CO₂ reached 368 ppm and this increased to 388 ppm in 2010 (Rackley, 2017). Currently, the amount of CO₂ is increasing by two ppm per year in the atmosphere, suggesting that CO₂ emitted remains in the atmosphere. The atmosphere may contain up to 570 ppm of CO₂ in 2100 causing a rise of approximately 3.2 °C in the mean global temperature and an increase of 3.8 m in the mean sea level according to the Intergovernmental Panel on Climate Change (IPCC). There are four potential sources of CO₂ emission

which are from the industrial processes, fossil-fueled power plants, de-carbonization and transportation. Among the CO₂ emission sources, fossil-fueled power plants are the main source of CO₂ with 81 % of the world's commercial energy supply (Carpanez *et al.*, 2024). The fossil fuel emission level is shown in Table 1.1.

Table 1.1. Fossil fuel emission levels (IEA, 2024).

Pollutant	Natural Gas	Coal	Oil
Carbon dioxide	117000	208000	164000
Carbon monoxide	40	208	33
Nitrogen oxides	92	457	448
Sulphur dioxide	1	2591	1122
Particulates	7	2744	84
Mercury	0	0.016	0.007
Total	117140	214000	165687

1.1.2 CO₂ capture

There are several approaches that can be implemented to reduce the total CO₂ emission in the atmosphere such as improving energy efficiency to lower energy intensity, reducing carbon intensity through the use of alternatives fuels such as hydrogen and renewable energy source and enhancing CO₂ sequestration by developing advanced carbon capture materials (Min *et al.*, 2022). CO₂ capture and storage (CCS) have been receiving significant attention in recent years and are being recognized as promising options for CO₂ emission reduction (Turgut *et al.*, 2022). Adsorption is the most suitable technologies for CO₂ capture from atmosphere than other technologies that is widely used in CCS process. Recently, the capture of CO₂ directly from atmosphere has generated extensive research interest (Wu *et al.*, 2024). Two approaches are currently being used to capture CO₂ from the atmosphere which is through solid and liquid adsorbents. Liquid adsorbent relies on an aqueous basic solution such as potassium hydroxide operating at high temperature (300–900 °C). Meanwhile, solid adsorbent is based on solid materials that function effectively at

ambient temperature and pressure. Unlike liquid systems, solid adsorbents do not pose issues related to corrosion or water loss, making them a more practical and energy-efficient alternative for atmospheric CO₂ capture.

In recent years, CO₂ adsorption using dry regenerable solid adsorbents has emerged as an advanced strategy for carbon capture. Various microporous and mesoporous solid adsorbents have been explored for CO₂ capture including, metal oxides, hydrotalcite like compounds, carbon-based materials, zeolites and metal-organic frameworks (MOFs) (Petrovic *et al.*, 2021). These studies not only focus on enhancing the material properties and performance but also with functional group modification and stability enhancement of the materials with the help of effective methods (Khosrowshahi *et al.*, 2024). An ideal adsorbent should exhibit high CO₂ adsorption performances, while also being cost-effective, scalable and fast kinetic performance. Metal oxides have shown great potential and emerged as promising materials for CO₂ adsorption due to their favorable structural and chemical properties. Many metal oxides possess a large specific surface area and a high number of active sites which facilitate effective interaction with CO₂ molecules and advantageous in adsorption (Ong *et al.*, 2018). Their surface basicity is particularly important for binding acidic CO₂ molecules through chemisorption or carbonate formation. Furthermore, metal oxides are widely available and making them attractive candidates for large-scale CO₂ capture technologies (Gao *et al.*, 2024; Ma *et al.*, 2025). The remarkably high CO₂ capture capacities in metal oxides can be ascribed to the strong affinity of metal cations towards CO₂ molecules as well as the Lewis basic sites presented on the surface of metal oxides.

The doping and structural modification have attracted continuous research interest as a method to enhance the performance of metal oxides (Wu *et al.*, 2025). The limited adsorption capacity on metal oxides is the main reason driving these efforts as introducing dopants or modifying the crystal structure can increase the surface area, creates additional active sites and improves pore structure. However, excess additional active sites give pore-blockage during surface functionalization modification. This blockage can cause steric hindrance, impeding the diffusion of CO₂ molecules into the adsorbent. Consequently, the overall efficiency of CO₂ adsorption can be compromised. Thus, several supports were used as impregnated for CO₂ adsorbents such as activated carbon (AC), silica, carbon nanotubes and halloysite nanotubes (HNTs) (Jena *et al.*, 2019; Khandaker *et al.*, 2020; Sharma *et al.*, 2021; Kamran and Park, 2021). The impregnation metal oxides using natural clay mineral is effective in rectifying the issues that arise during the adsorption (Khoshraftar *et al.*, 2021). Impregnation provides higher CO₂ adsorption capacity and more efficient capture performance. Expanding the production and development of adsorbents with abilities such as enhancing adsorption capacity, cost-effectiveness and high efficiency is one of the efficient solutions to meet the challenges of CO₂ capture (Adhikari *et al.*, 2018; Taheri *et al.*, 2019). The impregnation with supporting materials has been regarded as a constructive strategy that has garnered considerable attention due to its availability, reliability, low cost and high stability of the adsorbent.

1.2 Problem statement

Environmental pollution has become a serious issue due to the rapid development of urbanization and industrialization. Notably, this issue significantly contributes to rising atmospheric CO₂ levels. To address this problem, various CCS technologies have been developed, aiming to reduce CO₂ emissions and mitigate their

impact on climate change. There is a great need to develop a low-cost and effective solid adsorbent for the safety of environment.

Besides CaO and amine-based solids, ferrite-based oxides is one of the promising adsorbents owing to its low price, chemical stability, and tunable structural properties. However, despite its versatility, ferrite-based oxides exhibit relatively lower CO₂ adsorption capacity compared to advanced materials such as amine-functionalized adsorbents or metal-organic frameworks (MOFs) (Bagherinasab *et al.*, 2020). This limitation is primarily linked to factors such as restricted surface area, suboptimal pore structures, and insufficient active site availability. To date, most single metal oxide adsorbents cannot meet the demands to capture high amounts of CO₂ from the atmosphere (Hakim *et al.*, 2016). Therefore, these issues must be addressed for high adsorption performance and for practical application of ferrite-based oxides. A systematic approach is applied by comparing single ferrite-based oxides with different crystal structure (ternary and quaternary) to evaluate their structural influence on CO₂ adsorption. Despite all extensive studies, the application of ternary and quaternary ferrite-based oxides specifically for CO₂ adsorption remains largely unexplored.

Additionally, the application of ferrite-based oxides for CO₂ adsorption faces the inherent challenge of limited adsorption capacity, primarily due to their insufficient surface area and number of active sites. This limitation drives the need for structural modifications, such as doping or crystal structure adjustment, to enhance surface area, create additional active sites, and improve pore structure for more effective CO₂ capture. However, during doping or surface modification, the introduction of excessive active sites may lead to pore blockage, causing steric hindrance that limits the diffusion of CO₂ molecules into the adsorbent structure (Elvira *et al.*, 2017). Thus, impregnation

of adsorbent onto a support is one of the alternatives to overcome this problem. This approach could minimize the percentage of adsorption capacity loss during reusability by enhancing structural stability, and maintaining accessible pore structures throughout multiple adsorption–desorption cycles, ultimately improving the long-term performance and economic viability of the CO₂ capture process.

While sol-gel methods have been widely employed for the synthesis of ferrite–based oxides due to their simplicity, cost-effectiveness, and ability to control particle size, crystallinity, and porosity, this approach presents challenges. The process relies on chelating agents such as citric acid (CA) or others to form stable metal–ligand complexes, ensuring homogeneous mixing and preventing unwanted precipitation. However, the method is highly sensitive to reagent ratios and pH control. An adequate amount of chelating agent is required to complete chelation, but excessive it can create an overly acidic environment that disrupts its own dissociation, complicating gel formation. Careful pH adjustment, often using ammonia is necessary to maintain the equilibrium for proper sol formation. However, even minor deviations in pH or reagent balance can result in unwanted precipitation rather than forming a stable sol, making the process less consistent and more difficult to scale for practical CO₂ adsorption applications. Therefore, the optimized condition needs to be established to ensures consistent and reproducible synthesis outcome by precisely controlling key parameters. This optimization not only minimizes issues but also makes the process more reliable and scalable for practical carbon capture applications.

1.3 Research objectives

The main aim of this research is to synthesis ferrite-based oxide adsorbents using a sol-gel method for CO₂ capture at low temperature. There are several objectives for this research as listed below.

1. To prepare, characterise, and compare the CO₂ adsorption performance of ferrite-based oxides adsorbents, NiFe₂O₄, BaFe₁₂O₁₉ and BaNi₂Fe₁₆O₂₇ prepared by sol gel method.
2. To prepare, characterise, and compare the CO₂ adsorption performance of Al-doped BaNi₂Fe_{16-x}Al_xO₂₇ ($0.3 \leq x \leq 1$) with the undoped at low temperatures under TGA analysis.
3. To prepare and characterize the impregnated halloysite nanotubes/aluminium doped barium nickel ferrite (HNT/BaNi₂Fe_{16-x}Al_xO₂₇) composite adsorbents using various wt % of BaNi₂Fe_{16-x}Al_xO₂₇ ($x=1.0$).
4. To investigate the potential of HNT/BaNi₂Fe_{16-x}Al_xO₂₇ composite adsorbent towards the CO₂ adsorption capacity followed by the optimization of the reaction conditions and kinetics involved during the low temperature of adsorption activities.

1.4 Significance of study

This study highlights the development of ferrite-based oxides as sustainable and efficient adsorbents for CO₂ capture applications. The employment of the sol-gel method as the synthesis route offers simple, cheaper and controllable processing approach which helps to offers a reliable and efficient route. The use of ferrite-based oxides as CO₂ adsorbent with precise control and optimized on synthesis condition by regulating parameters such as chelating agent ratio, pH balance, and calcination

temperature in the preparation of ferrite-based oxide suggests a more feasible technique with regards to achieving enhanced surface area, and improved phase purity, while also ensuring better reproducibility, scalability, and energy efficiency in CO₂ capture. The improved method after the optimization eliminates the need for excessive amounts of chelating agents and removes the cumbersome requirement for real-time pH adjustment such as using ammonia water. The preparation process is greatly simplified minimizes issues like uncontrolled precipitation, and inconsistent phase formation.

Additionally, the introduction of metal dopants in ferrite-based oxides such as aluminium (Al) is beneficial as it is an effective strategy in enhancing the structure of ferrite-based oxides, addressing the limited CO₂ adsorption capacity typically observed on metal oxides. Al is easily available and abundant as a metal dopant is more practical and cost-effective to the adsorbent. Its small ionic radius and ability to integrate into the ferrite lattice contribute to improved structural stability, surface area, and porosity, making it ideal for enhancing CO₂ adsorption performance. Furthermore, the impregnation of porous and naturally supporting materials such as halloysite nanotubes (HNT) is favored and exceptionally advantageous as it possesses high reusability and a large specific surface area that gives benefits on adsorption application. Their unique tubular morphology and abundant surface functional groups provide additional active sites and facilitate better dispersion of the ferrite-based oxides, minimizing agglomeration. Additionally, the risk of pore blockage commonly encountered during surface modification such as doping can be alleviated, as the open tubular channels of HNT help maintain accessible pathways for CO₂ molecules, ensuring efficient diffusion and maximizing adsorption capacity. This combination contributes to improved adsorption capacity with long-term operational efficiency,

making HNT-impregnated ferrite composites a promising option for sustainable CO₂ capture applications.

1.5 Scope of study

This study focuses on the development of cost effective and efficient ferrite-based solid adsorbent using a sol-gel method. Several preparation parameters were varied including the citric acid to metal ions (CA:MI) molar ratio, calcination temperature and duration to optimize the synthesis of the adsorbents. Additionally, the study explores the doping of the ferrite-based oxide with aluminium (Al) to enhance the basicity and surface properties, which are important for CO₂ adsorption. Furthermore, the adsorbents were impregnated with HNTs to improve structural stability, increase surface area, and enhance the adsorption kinetics. These modifications aim to enhance the CO₂ capture performance of the adsorbent by increasing its active sites and maintaining structural properties during multiple adsorption-desorption cycles. The adsorbents were characterized using various techniques such as X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy-energy dispersive X-ray spectroscopy (SEM-EDX), nitrogen adsorption-desorption (NAD), X-ray photoelectron spectroscopy (XPS), thermogravimetric analysis (TGA) and temperature-programmed desorption (CO₂-TPD). The adsorption parameters (effect of adsorption temperature, adsorbent loading and gas flow rate), recyclability, kinetics and thermodynamic study were also presented.

1.6 Thesis layout

This thesis is structured into seven chapters. Chapter 1 (Introduction) describes the general overview of the work about climate change and CO₂ emission in atmosphere. The overview of the entire thesis including the problem statements, research objectives and scope of the study have been presented to summarize the content of the thesis. Chapter 2 (Literature Review) elaborates about different types of solid adsorbent for CO₂ capture and most importantly ferrite-based adsorbents that have been developed. Subsequently, an overview of the CO₂ capture technologies in the atmosphere that available these days have been explained. Chapter 3 (Experimental) presents the research methodology, which includes the materials and chemicals. The characterization techniques used to analyze the adsorbents have also been described in this chapter. Experimental design for CO₂ adsorption study also presented in this section. Chapter 4 (Results and Discussions) discusses the synthesis and optimization of synthesis parameters of ferrite-based oxides. Characterization analyses and CO₂ adsorption performance are also presented. In Chapter 5, the characterization of structural, morphological as well as the findings on the CO₂ adsorption for Al-doped BaNi₂Fe₁₆O₂₇ ($0.3 \leq x \leq 1$) at low temperatures are compared and discussed. Chapter 6 outlines the characterization of the impregnated HNT/BaNi₂Fe_{16-x}Al_xO₂₇ adsorbent at various wt %. The findings on the CO₂ adsorption capacity of HNT/BaNi₂Fe_{16-x}Al_xO₂₇ are discussed and compared. Finally, Chapter 7 (Conclusion and Recommendation) concludes the major findings of the study and some recommendations for future works are also presented.

CHAPTER 2

LITERATURE REVIEW

2.1 Impact of industrialization on CO₂ emission and climate change

Environmental issues due to the emission of pollutants have increased due to heavy pollution from industrial facilities since the beginning of the industrial revolution. Most of the pollution is the result of burning fossil fuel (coal, crude oil and natural gas) (Olajire *et al.*, 2010; Koirala *et al.*, 2011; Lee *et al.*, 2021; Donaghy *et al.*, 2023). Today, one of the most challenging and urgent environmental issues that needs to be addressed is the increase of CO₂ concentration in the atmosphere which is widely reported to be the main anthropogenic greenhouse gas (GHG) that leads to global warming and climate changes (Mar *et al.*, 2022; Yusuf *et al.*, 2023). The amount of CO₂ is increasing by two ppm per year in the atmosphere which suggests that more than a third of the CO₂ emitted remains in the atmosphere. In 2020, the average annual level of CO₂ in the atmosphere was approximately 50 % higher than in the 60's and has attained the greatest value recorded in history of 412.55 ppm (IEA, 2021).

Unfortunately, the rapid development of the world's economy, accelerating industrialization as well as, soaring world population will continuously cause a gradual growth of CO₂ emissions and will affect global warming in the next 30 years at the current state (Sinehbaghizadeh *et al.*, 2022; Dziejarski *et al.*, 2023; Guo *et al.*, 2023). According to the Intergovernmental Panel on Climate Change (IPCC) report in 2022, climate change mitigation efforts should be executed immediately to prevent this scenario. IPCC estimation indicates that the peak of GHG emissions must take place in 2025 at the latest and by 2030 a 43 % reduction of it will possibly be achieved.

Otherwise, by the end of 2100 the average temperature on Earth and atmospheric concentration of CO₂ will increase by 3.2 °C and 570 ppm, respectively (Shukla *et al.*, 2022). Hence, in order to prevent this occurrence, specific energy management should be adopted. In particular, innovative transformation should be done by industries which are responsible for 25 % of CO₂ emissions (IEA, 2019).

In view of this, for the last several decades there have been initiatives to create new systems for carbon capture aiming to reduce CO₂ emission from entering the atmosphere. These systems are known as carbon capture, utilization and storage (CCUS) which can be divided into carbon capture and storage (CCS), carbon capture and utilization (CCU) and bioenergy with carbon capture and storage (BECCS). In these systems both liquid and solid adsorbents play a crucial role in the capture of CO₂.

2.2 Current materials for CO₂ capture

Solid and liquid adsorbents are two approaches used to capture CO₂ from the atmosphere. Liquid adsorbents require high temperatures of 300–900 °C to capture CO₂. Adsorbents such as aqueous amino acids, aqueous monoethanolamine (MEA), ionic liquids (ILs) and aqueous solution of hydroxides, are commonly used to capture CO₂ in industries (Xiao *et al.*, 2021). The advantage of liquid adsorbents is that they are effective in capturing CO₂. However, the corrosive effect of liquid adsorbents affects the service life of the equipment. Another drawback is that liquid adsorbents can react chemically with other acid gases resulting in less active CO₂ being adsorbed. In contrast to liquid adsorbents, solid adsorbents can capture CO₂ at ambient pressure with temperatures range starting from room temperature. Furthermore, solid adsorbents are less corrosive and does not require the treatment of large volumes of aqueous phase.

Several important definitions that should be used in the CO₂ adsorption process. Adsorbent is defined as a solid or liquid on which gas molecules are adsorbed and adsorbate is a gas that is adsorbed on the surface of the adsorbent (Santamaria *et al.*, 2023). There are two main types of gas molecule adsorption on the surface of a solid. If the accumulation of the adsorbate on the surface of the solid occurs due to weak intermolecular van der Waals interaction, then adsorption is termed physisorption or physical adsorption (Ghaedi, 2021). Meanwhile, when gas molecules accumulate on the surface of the adsorbent by chemical bond, the phenomenon occurring is called chemical adsorption or chemisorption (Tatarchuk *et al.*, 2023).

2.3 Liquid adsorbents

2.3.1 Aqueous amino acids

Aqueous amino acids have been investigated for CO₂ capture as liquid adsorbent as it is relatively non-volatile, environmentally friendly and can be regenerated using mild heating (≈ 100 °C). For instance, Custelcean and co-workers (2019) reported using amino acid-based adsorbents with a capacity of 0.7 mol of CO₂ mol⁻¹ of aqueous solution in ambient air conditions. The CO₂ capture reaction of this adsorbent is shown in Figure 2.1. In this study, the CO₂-saturated species in the solution were then crystallized using 2,6-pyridine-bis(iminonoguanidine) to form a solid hydrated carbonate in an aqueous solution. Three consecutive adsorption and regeneration cycles were conducted with observed low cyclic capacities of 0.12–0.20 CO₂ mol⁻¹ and a measured regeneration energy demand of 360 kJ mol⁻¹. The adsorbent system offers a notable advantage due to its substantially lower generation temperatures (60–120 °C) compared to CaCO₃ (900 °C). However, the energy demand surpasses the corresponding energy for the CaCO₃ direct air capture (DAC) benchmark

(278 kJ mol⁻¹) hence becomes energetically less efficient. Higher regeneration energy demand indicates more energy required to restore the adsorbent after the adsorption process, making it less economically viable. Recker *et al.* (2022) also reported that amino acids as adsorbents usually present low cyclic capacities which are typically in the range of 0.12–0.40 mol CO₂ mol⁻¹ adsorbent. However, amino acids with basic functional group are desirable liquid adsorbent for CO₂ capture (Ramezani *et al.*, 2022).

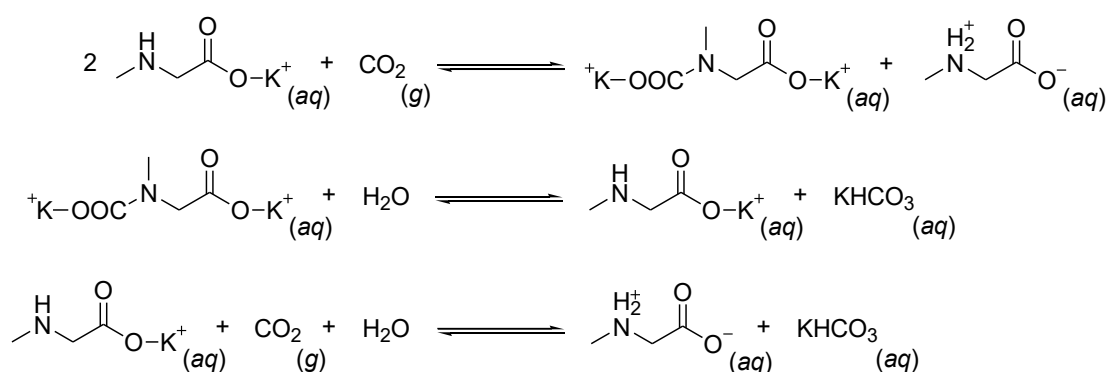


Figure 2.1 CO₂ capture reaction with aqueous amino acids (Custelcean *et al.*, 2019).

2.3.2 Aqueous monoethanolamine (MEA)

MEA is one of the most researched liquid adsorbents for CO₂ capture from atmosphere. However, MEA suffers from a series of inherent problems including corrosive nature of the amines and the need for high regeneration energy. MEA was reported to be inefficient in capturing CO₂ at concentrations of 400 ppm (Lee *et al.*, 2023). Meanwhile, this adsorbent was reported to have lower adsorption rate compared to other alkaline liquid adsorbents such as potassium carbonate (K₂CO₃) and piperazine (secondary amine). It degrades when exposed to oxygen and is environmentally unfriendly (Abdullatif *et al.*, 2023). A recent study of different MEA under 0.044 % of CO₂ in air was conducted (Barzagli *et al.*, 2020). In this screening

study, several MEA particularly those already known for their utilization in CCS were tested. The percentage of CO₂ adsorption was evaluated in 24 hours capture experiments and the species formed were identified and quantified using NMR spectroscopy. The correlation between chemical structures of the different amines and the species formed in solution showed that a high yield production of amine carbamate is the decisive factor for an effective CO₂ capture (Barzagli *et al.*, 2020). Despite their effectiveness in capturing CO₂, the use of this adsorbent potentially may pose environmental hazards. The common environmental concerns include toxicity and potential persistence in the environment. It is crucial to carefully manage the environmental impact of any adsorbent to ensure that the benefits of CO₂ capture are not outweighed by negative environmental consequences.

2.3.3 Ionic liquids (ILs)

Other adsorbents that have potential for CO₂ capture from atmosphere are ionic liquids (ILs). This is due to their low melting point and the ability to tailor their properties by structural manipulations. Several research activities have been reported to investigate ILs as substitutes for MEA as adsorbents for CO₂ capture (Perumal *et al.*, 2021; Zhang *et al.*, 2022; Bisht *et al.*, 2023). This is mainly due to their relatively lower regeneration energy and low volatility (Ma *et al.*, 2021).

Chen and co-workers (2017) reported the adsorbent for CO₂ capture from atmosphere involving ionic liquid [P4444][p-2-O] and pyrene-based conjugated polymer (IL-CP). The adsorbent was reported to be capable of efficiently adsorbing CO₂ under ambient conditions. The stability and reusability of the IL-CP were examined and it could be regenerated and reused to adsorb CO₂ from atmosphere for

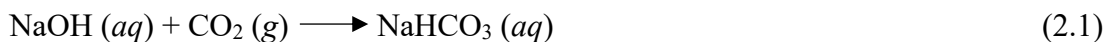
at least five times. The results indicate that the IL-CP was stable and reusable. However, the process involved is difficult to scale up and very costly.

To date, numerous studies have also demonstrated remarkable CO₂ adsorption using ILs such as imidazolium, pyridinium and pyrrolidinium based cations as well as fluoroalkyl based anions (Perumal *et al.*, 2021; Ab Rahim *et al.*, 2023). Most commonly fluorinated anions possess excellent features owing to their low reactivity and high chemical stability. However, fluorinated anions are expensive, have low thermal stability and release toxic compounds which is a major environmental concern (Han *et al.*, 2021).

2.3.4 Aqueous solution of hydroxides

The latest liquid adsorbents for CO₂ capture involve the use of aqueous solutions such as sodium hydroxide (NaOH), calcium hydroxide (Ca(OH)₂) and potassium hydroxide (KOH) (Keith *et al.*, 2018; Leonzio *et al.*, 2022; Abanades *et al.*, 2023). The usage of NaOH for CO₂ adsorption has been studied intensively and has an excellent CO₂ adsorption capacity. Ghaffari *et al.*, (2023) investigated the CO₂ capture efficiency of NaOH at varying wt %. In this study, a NaOH system with a concentration between 3 to 10 wt % was used to capture a gas mixture with diluted CO₂ (0.0153–1.2 vol %). The obtained results show the maximum amount of adsorption capacity at 6 wt % NaOH. It was deduced that the CO₂ capture efficiency in a NaOH system is highly dependent on the concentration of the solvent. However, aqueous NaOH adsorbent cannot be easily regenerated due to the formation of NaHCO₃ when reacted with CO₂. Besides, NaHCO₃ has high solubility in an aqueous solution. Its decomposed product, Na₂CO₃ is a thermally stable compound that can be

decomposed to Na₂O at a temperature of over 800 °C. The overall CO₂ adsorption reaction with NaOH is as follows:



Ca(OH)₂ aqueous solution has the potential to be an effective adsorbent for CO₂ capture due to relatively low in cost. These materials are inexpensive and non-hazardous to the environment. The experiment conducted by Pinto *et al.*, (2019) on CO₂ capture by pure Ca(OH)₂ shows the adsorption capacity of 0.786 CO₂ g⁻¹. This study then modified the Ca(OH)₂ based materials with magnesium oxide and ammonium phosphate. The result showed an increment of 50 wt % of CO₂ adsorption capacity. However, this adsorbent has not received much interest as the regeneration process of Ca(OH)₂, is energy-intensive. To regenerate Ca(OH)₂, CaCO₃ needs to undergo a calcination process at a high temperature (650–765 °C) to obtain CaO which is a direct source of Ca(OH)₂.

Additionally, KOH has also been included as an aqueous hydroxide adsorbent (Smith *et al.*, 2019). However, the research on KOH is only limited to its CO₂ performance data. A detailed description of its CO₂ capture mechanism is still not available (Ngu *et al.*, 2019; Chai *et al.*, 2022). This necessitates further exploration of alternative adsorbents to enhance efficiency in the CO₂ capture process.

2.4 Criteria for selecting solid CO₂ capture materials

Several criteria are significant in selecting suitable solids for CO₂ capture (Figure 2.2). Among these, crystallinity plays an important role in the selection of materials for CO₂ capture. The organized crystalline structure contributes to the formation of well-defined pores which enhance the ability to capture CO₂ because of

its high surface area. Meanwhile, amorphous materials lack long-range order in their atomic or molecular arrangement. The structure is more random with no distinct repeating pattern, resulting in a lower surface area. This may limit the number of active sites available for CO₂ capture. Ultimately, the choice between crystalline and amorphous materials hinges on the specific demands of CO₂ capture applications and desired performance. Joutsuka and Tada, (2023) studied the adsorption behavior of CO₂ on amorphous and crystalline zirconia. The XRD analysis and CO₂-TPD experiment indicates that adsorption of CO₂ on amorphous zirconia is weaker than that on a crystalline zirconia surface. In 2023, Ma and co-workers (2023) studied the CO₂ adsorption capacity of crystalline SiO₂ and amorphous SiO₂. The adsorption capacity test revealed that crystalline SiO₂ adsorbed about 23 % more CO₂ than amorphous SiO₂.

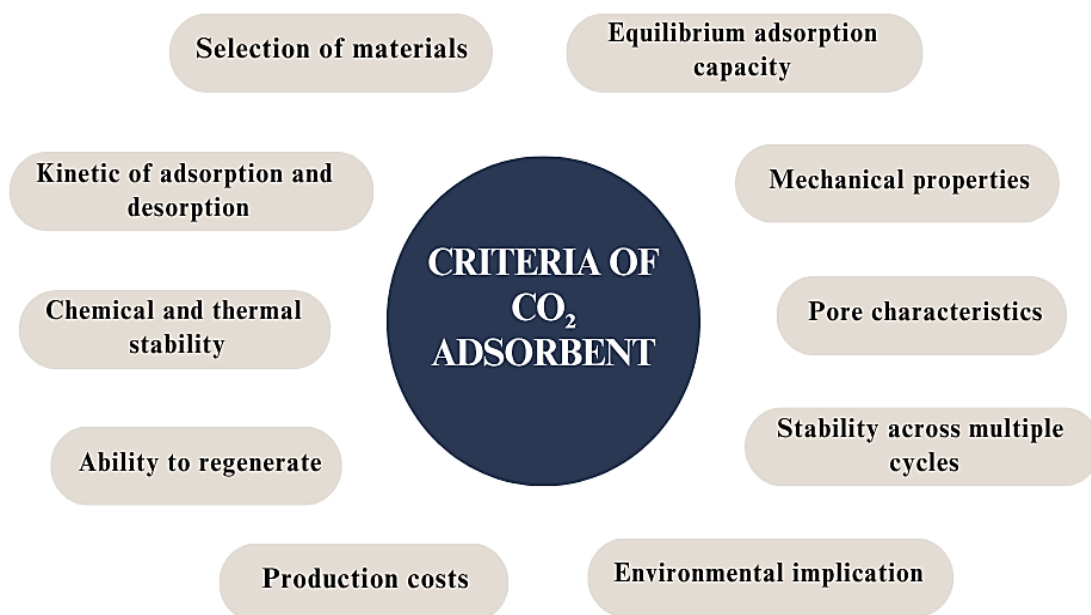


Figure 2.2 The important properties and criteria for selecting CO₂ capture materials.

The adsorption capacity is also related to pore size and surface interaction of the adsorbent. The pore size of an adsorbent is crucial as it determines the accessibility and accommodation of CO₂ molecules in the adsorbent. Yao *et al.* (2023) investigated the effectiveness of CO₂ capture using CuCl₂-activated sustainable microporous carbon. Based on the analysis, high amounts of well-developed microporosity are effective in capturing CO₂. Optimizing the pore size and surface chemistry of the adsorbent is a key strategy to enhance adsorption capacity of CO₂.

Kinetics of adsorption and desorption is another important factor, so that adsorption and desorption can occur in a short span of time and the number of cycles can be increased. However, this is influenced by several factors including the porosity of the adsorbent, the concentration of adsorbate and the type of chemical bonding formed during the process. Martin *et al.* (2016) investigated an economic and simple method to manufacture low cost but effective adsorbents for CO₂ capture through impregnating diethylenetriamine (DETA) into a porous silica gel. Although the capacities were unremarkable, the authors were able to demonstrate fast kinetics and relatively stable cyclic performance. This is desirable as a short time is required to attain the equilibrium state between the adsorbate-adsorbent.

The adsorbent should also be mechanically strong and resistant to abrasion and crushing during adsorption. The adsorption process often involves dynamic conditions experiencing forces due to the flow of the adsorbate molecules. If the adsorbent lacks mechanical strength, it could break down or undergo structural changes compromising its efficiency and performance. Plaza *et al.* (2015) reported that the wood-based activated carbon (AC) exhibited potential as an industrial-level CO₂ adsorbent as it has high economical and adsorption efficiency with excellent mechanical resistance.

Mechanically strong adsorbent contributes to the reliability and longevity of the adsorption process. It ensures the adsorbent remains intact and effective over multiple cycles of adsorption and desorption.

Pore characteristics are an important feature for this application. There is a correlation between the type of pore and the gas molecules. Reddy *et al.*, (2021) developed a new adsorbent with bigger pores to enable fast transport and gas/surface interactions to capture CO₂. The modification or addition of specific functional groups to the porous adsorbent is aimed at enhancing the performance of adsorbents in terms of the ability to capture CO₂ effectively. Essentially, the specific pore structure of the adsorbent is a key determinant of its performance in adsorbing and transporting gases in this application.

Chemical and thermal stability are also important characteristics of an adsorbent especially when used at elevated temperatures. It is to ensure that it can be used for its proper lifetime with consistently high equilibrium adsorption capacity. Wang *et al.*, (2020) studied the thermal stability and CO₂ adsorption of ZIF-8 and its modification by using parallel flow-drop solvothermal method. Different amounts of -NH₂ (0, 6, 12 and 18 % NH₂-ZIF-8) was successfully introduced into the surface of ZIF-8 by modification with polyaniline. It was found that the decomposition temperature of 12 % doped content of polyaniline in NH₂-ZIF-8 slightly increased to 632.71 °C, suggesting their higher thermal stability compared to 0, 6 and 18 % doped content. The improvement of thermal stability after modification shows the increase in CO₂ adsorption of the adsorbent. The introduction of -NH₂ functional group into ZIF-8 can effectively change the electrostatic force between ZIF-8 and CO₂, thus improving the CO₂ adsorption property of ZIF-8.

Adsorbents usually undergo a regeneration process after the adsorption capacity is exhausted. The process of regeneration involves removal of the adsorbed CO₂ molecules from the pores and the surface by desorption. This will allow restoration of the adsorption capabilities of the adsorbent. The regeneration capability of a material is an important factor in determining the suitability of a material for CO₂ adsorption. The regeneration process is largely affected by temperature and pressure. The selection of optimal temperature and pressure parameters is crucial to ensure the successful release of adsorbed CO₂ from the adsorbent. The desorption process typically requires elevated temperatures to break the bonds between CO₂ molecules and the adsorbent surface. Higher temperatures can enhance the kinetics of desorption allowing for the efficient release of CO₂ and regeneration of the adsorbent for subsequent cycles. However, the choice of temperature needs to balance the need for effective desorption with energy considerations and adsorbent stability. Pressure also plays a role in the regeneration process, influencing the thermodynamics of desorption. Changes in pressure can impact the equilibrium between adsorbed and desorbed CO₂ affecting the efficiency of the desorption step. Optimal pressure conditions need to be determined to achieve effective and controlled release of CO₂ during regeneration. In summary, both are critical parameters in the regeneration process for CO₂ adsorption systems. Finding the right combination of these conditions is essential for maximizing the performance, energy efficiency and overall effectiveness of CO₂ capture technology.

The stability in adsorption and desorption cycles also play a crucial role in the adsorption process. High surface area of carbon adsorbents was prepared by KOH activation of carbonized PAN which exhibits CO₂ adsorption capacities in the range of 1.7–2.5 mmol g⁻¹ by Singh *et al.*, (2019). Based on analysis, the adsorbent exhibits

stable adsorption capacity (2.5 mmol g^{-1}) over five cycles of adsorption/desorption with no loss in efficiency. The cost is another crucial criterion that needs to be considered. The economic viability of the adsorbents is defined as the cost per unit mass of the raw materials used in the synthesis process (Sarafraz *et al.*, 2019). The cost of adsorbent preparation can be determined based on the cost of raw materials or industrial-grade precursors and the chemical used to process them (Kani *et al.*, 2020). Operational costs are also included as the cost factors in this application. Table 2.1 show the cost effectiveness and features of adsorbents for CO₂ capture.

Table 2.1 Cost effectiveness and features of adsorbents for CO₂ capture.

Adsorbent	Features	Price (USD \$/kg)
Activated Carbon	-Widely available -Thermally stable -Ease of regeneration -Require high operating pressure	~35.1 (Merck, 2023; Kumar <i>et al.</i> , 2020)
Metal organic frameworks (MOFs)	-Tunable pore structure -Large surface area -Ease of regeneration	~527.3 (Mubarak <i>et al.</i> , 2022; Cui <i>et al.</i> , 2023; Wang <i>et al.</i> , 2023)
Zeolite	-Universal availability -Thermally stable -High surface area -Low adsorption capacity	~3.5 (Chemxin, 2023; Bai <i>et al.</i> , 2022)
Silica	-Thermally and mechanically stable -Tunable pore structure -Improper reusability -Difficulty in large scale production	~12.2 (Zaed <i>et al.</i> , 2023; Pang <i>et al.</i> , 2023)
Metal oxide	-Widely available -Low toxicity	~32.5 (CaO, Bernd Kraft, 2023; Musa <i>et al.</i> , 2023)

The choice of adsorbent materials for CO₂ capture hinges on a balance between performance characteristics and cost-effectiveness. As shown in Table 2.1, activated carbon is widely used due to its high availability, thermal stability, and ease of regeneration. However, it typically requires high operating pressure for effective CO₂

capture, which can increase energy costs. With a moderate price of ~\$35.1/kg, it remains a cost-effective option for many industrial applications. Additionally, metal-organic frameworks (MOFs) are known for their exceptionally high surface area, tunable pore structures, and ease of regeneration, making them one of the most promising materials for CO₂ capture. However, their extremely high cost (~\$527.3/kg) and challenges in large-scale synthesis currently hinder widespread practical use. Zeolites, on the other hand, are among the cheapest options (~\$3.5/kg) and offer good thermal stability and high surface area, though they generally suffer from lower CO₂ adsorption capacities. Silica-based materials offer favorable characteristics such as high surface area, tunable pore structures, and thermal and mechanical stability. However, they also require high energy for regeneration, and are moderately priced at ~\$12.2/kg. Meanwhile, metal oxides are commonly used due to their low toxicity and widespread availability. This adsorbent has potential in economic feasibility due to its relatively affordable cost of ~\$32.5/kg. Overall, the ideal material depends on the specific application, operational conditions, and economic constraints.

2.5 Solid adsorbents

The application of solid adsorbent materials is regarded as one of the most promising research directions and has garnered a high amount of attention for carbon capture in CCUS (Dziejarski *et al.*, 2023). Solid adsorbents such as carbonaceous materials (Kamran and Park, 2021), metal-organic framework (MOFs) (Bertina *et al.*, 2022), zeolites (Kumar *et al.*, 2020), hydrotalcites (HTlcs) and metal oxides have gained popularity over liquid adsorbents due to benefits such as considerably high CO₂ uptake efficiency, easy regeneration, simple handling, material stability and low cost

(Paradakhti *et al.*, 2019). Figure 2.3 is the number of publications since 2013 that have concerned solid materials for CO₂ capture.

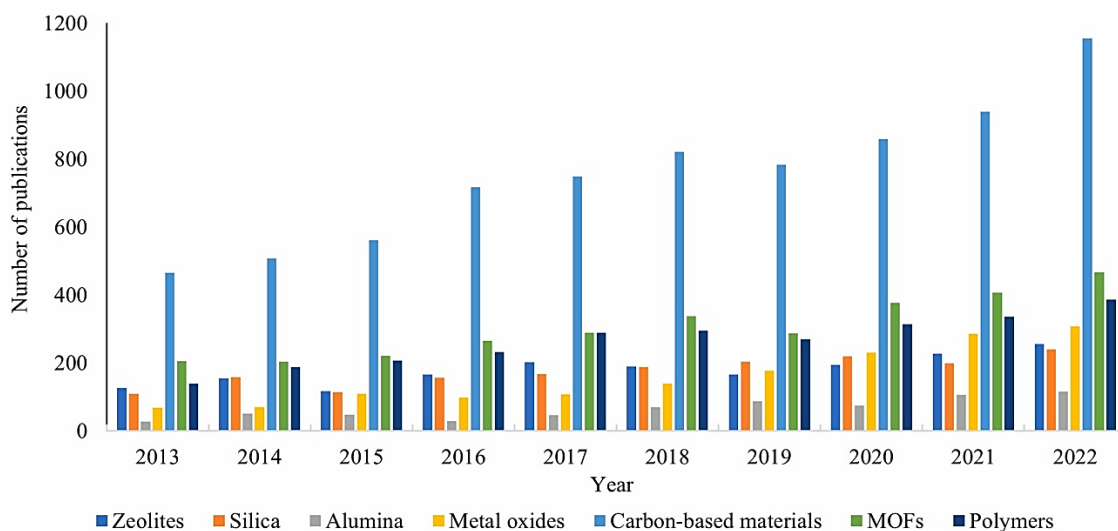


Figure 2.3 Number of publications on CO₂ capture with various solid adsorbents since 2013, based on Scopus with keywords “CO₂ adsorption” or “CO₂ capture” (Dziejarski *et al.*, 2023).

2.5.1 Carbonaceous materials

Owing to their low-cost, high surface area, high amenability to pore structure modification and surface functionalization, carbon-based materials are considered to be one of the most promising adsorbents for capturing CO₂. However, the CO₂ adsorption on carbon materials is physical and weak which makes these adsorbents sensitive to temperature and pressure with relatively poor selectivity. Thus, current research efforts are focused on how to enhance the adsorbate-adsorbent interaction and the selectivity for CO₂. One approach is to increase the surface area and tune the pore structure of carbon adsorbent either by using different precursors or forming different structures. Jin *et al.*, (2022) studied the adsorption of CO₂ from sawdust waste in ambient conditions. This study was undertaken to prepare low-cost sawdust wastes with different preparation parameters including sawdust type, activating agent,