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STATE NON-COMMERCIAL ENTERPRISE
STATE UNIVERSITY “KYIV AVIATION INSTITUTE”
FACULTY OF ENVIRONMENTAL SAFETY,
ENGINEERING AND TECHNOLOGIES
DEPARTMENT OF ENVIRONMENTAL SCIENCE

APPROVED TO DEFENCE
Head of the Graduate Department
_____________ Tamara DUDAR
“_____” ____________ 2025

BACHELOR THESIS

(EXPLANATORY NOTE)

Theme: «Greenhouse gases utilization efficiency»

Done by: seeker of Б-2021-21-1-ЕК group, Anastasiia S. Shestopal
(student, group, surname, name, patronymic)

Supervisor: Ph. D. in. Sc., Associate Professor of the Ecology Department, Marharyta M. Radomska
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KYIV 2025

МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ
ДЕРЖАВНЕ НЕКОМЕРЦІЙНЕ ПІДПРИЄМСТВО
«ДЕРЖАВНИЙ УНІВЕРСИТЕТ «КИЇВСЬКИЙ АВІАЦІЙНИЙ ІНСТИТУТ»
ФАКУЛЬТЕТ ЕКОЛОГІЧНОЇ БЕЗПЕКИ,
ІНЖЕНЕРІЇ ТА ТЕХНОЛОГІЙ
КАФЕДРА ЕКОЛОГІЇ

ДОПУСТИТИ ДО ЗАХИСТУ
Завідувач кафедри
_____________ Тамара ДУДАР
«_____» ____________ 2025 р.

КВАЛІФІКАЦІЙНА РОБОТА

(ПОЯСНЮВАЛЬНА ЗАПИСКА)

ВИПУСКНИКА ОСВІТНЬОГО СТУПЕНЯ «БАКАЛАВР»

Тема: “Ефективність утилізації парникових газів”

Виконавець: здобувачка групи Б-2021-21-1-ЕК Шестопал Анастасія Сергіївна

Керівник: К.т.н., доцент кафедри екології та охорони навколишнього середовища Маргарита Мирославівна Радомська

Нормоконтролер: ___________ Андріан ЯВНЮК

КИЇВ 2025

STATE NON-COMMERCIAL ENTERPRISE
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Faculty of Environmental Safety, Engineering and Technologies

Department of Environmental Science
Specialty, Educational and Training Program: specialty 101 “Environmental Science”, Educational and Training Program: “Ecology and Environment Protection”
(code, name)

APPROVED
Head of the Department
________Tamara DUDAR
«____» _________ 2025

BACHELOR THESIS ASSIGNMENT

Anastasiia S.Shestopal

1. Theme: «Greenhouse gases utilization efficiency»
approved by the Acting President on April, 28 2025 №634/ст
2. Duration of work: from 28.04.2025 to 17.06.2025.

3. Output data of work: results of the study of photocatalysis. Comparison of methods according to the MCDA-LCA methodology.

4. Content of explanatory note: the problem of utilization of greenhouse gases in the atmosphere. Utilization of greenhouse gas methods. Comparative analysis of the efficiency of greenhouse gas utilization methods.

5. The list of mandatory graphic (illustrated) materials: 7 tables, 3 graphic illustrations,

3 chapters.

6. Schedule of thesis performance

№ з/п	Task	Term	Advisor's signature
1	Collection and analysis of materials	28.04.2025 - 1.05.2025	
2	Literature review	2.05.2025 - 8.05.2025	
3	Writing chapter I of bachelor thesis	9.05.2025 - 18.05.2025	
4	Writing chapter II of bachelor thesis	19.05.2025 - 27.05.2025	
5	Writing chapter III of bachelor thesis	27.05.2025 - 5.06.2025	
6	Preliminary defense of the thesis	09.06.2025	
7	Registration of the thesis and work with the supervisor	11.06.2025	
8	Delivery of the finished thesis to the department	13.06.2025	
9	Presentation of the thesis	17.06.2025	

7. Date of task issue: «28» April 2025

Thesis supervisor: ________________ Marharyta RADOMSKA

(advisor's signature) (name, surname)

Task is taken to perform: ________________ Anastasiia SHESTOPAL

МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ
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Факультет екологічної безпеки, інженерії та технологій

Кафедра екології

Спеціальність, освітньо-професійна програма: спеціальність 101 «Екологія», ОПП «Екологія та охорона навколишнього середовища»

(шифр, найменування)

ЗАТВЕРДЖУЮ
Завідувач кафедри
___________Тамара ДУДАР
«____» _________ 2025 р.

ЗАВДАННЯ
на виконання кваліфікаційної роботи

Шестопал Анастасії Сергіївни

1. Тема кваліфікаційної роботи «Ефективність утилізації парникових газів» затверджена наказом в.о. президента від 28.04.2025 №634/ст

2. Термін виконання роботи: з 28.04.2025 по 17.06.2025.

3. Вихідні дані роботи: результати лабоpатрного дослідження фотокаталізу. Порівняння методів за методологією MCDA-LCA.

4. Зміст пояснювальної записки: Проблема утилізації парникових газів у атмосфері. Утилізація парникових методів. Порівняльний аналіз ефективності методів утилізації парникових газів.

5. Перелік обов’язкового графічного (ілюстративного) матеріалу: 7 таблиць, 3 графічні ілюстрації, 3 розділи.

6. Календарний план-графік

№ з/п	Завдання	Термін виконання	Підпис керівника
1	Збір та аналіз матеріалів	28.04.2025 - 1.05.2025	
2	Огляд літературних джерел	2.05.2025 - 8.05.2025	
3	Написання І розділу дипломної роботи	9.05.2025 - 18.05.2025	
4	Написання ІІ розділу дипломної роботи	19.05.2025 - 27.05.2025	
5	Написання ІІІ розділу дипломної роботи	27.05.2025 - 5.06.2025	
6	Попередній захист дипломної роботи	09.06.2025	
7	Оформлення дипломної роботи та робота з нормконтролером	11.06.2025	
8	Здача готової дипломної роботи на кафедру	13.06.2025	
9	Захист дипломної роботи	17.06.2025	

7. Дата видачі завдання: «28» квітня 2025 р.

Керівник кваліфікаційної роботи: ____________ Маргарита РАДОМСЬКА

(підпис керівника) (П.І.Б.)

Завдання прийняв до виконання: ____________ Анастасія ШЕСТОПАЛ

(підпис випускника) (П.І.Б.)

ABSTRACT

Explanatory note to thesis «Comparison of greenhouse gas disposal method» contains: 64 pages, 3 figures, 7 tables, 35 references.

Object of research: focuses on the process of greenhouse gases – carbon dioxide and methane conversion using environmentally sustainable technologies, with special attention to photocatalytic methods.

Aim of work: to conduct a comparative analysis of current greenhouse gas utilization technologies, assess their compliance with green chemistry principles, and experimentally investigate the environmental performance of carbon dioxide photocatalytic conversion.

Methods of research:

1. Multi-criteria decision analysis (MCDA-LCA);
2. Comparative method based on environmental and technical indicators;
3. Experimental photocatalytic testing in laboratory conditions;
4. Analytical modeling of process efficiency.

KEY WORDS: GREENHOUSE GASES, CARBON DIOXIDE, METHANE, GREEN CHEMISTRY, PHOTOCATALYTIC CONVERSION, THERMOCHEMICAL CONVERSION, CHEMICAL CONVERSION, DIRECT AIR CAPTURE, DRY METHANE REFORMING, MCDA-LCA TECHNOLOGY, UTILIZATION.

CONTENT

LIST OF SYMBOLIC NOTATIONS, ABBREVIATIONS AND NOTIONS

MCDA-LCA – Multi-criteria decision analysis;
UNFCCC – UN Framework Convention on Climate Change;
JI – Joint Implementation;
CDM – Clean Development Mechanism;
IET – International Emissions Trading;
HFCs – hydrofluorocarbons;
PFCs – perfluorocarbons;
GWP – global warming potential;
IPCC – Intergovernmental Panel on Climate Change;
MEA – monoethanolamine;
TPP – thermal power plant;
GHG – greenhouse gas;
DAC – Direct Air Capture;
DRM – dry reforming of methane;
TMC – thermochemical methane conversion;
MOFs – metal-organic frameworks.

INTRODUCTION

Relevance of the work: from the point of view of the strategic global goal of achieving net-zero greenhouse gas emissions by 2050, as set out in the Paris Agreement and supported by the European Green Deal. The efficient use of CO_2 and CH_4 by environmentally safe methods is a key technological direction for achieving carbon neutrality. Integrating these approaches with green chemistry principles, including waste prevention, energy efficiency and the use of renewable raw materials, improves both the environmental impact and industrial applicability. This research contributes to the scientific assessment of such technologies and their potential role in sustainable environmental policies.

Aim and the tasks of diploma work: conduct a comparative analysis of modern greenhouse gas utilization technologies, assess their compliance with the principles of green chemistry, and investigate the environmental parameters of photocatalytic conversion of CO_2 via experimental study.

Objectives of the work:

1. Analyze global and national trends in greenhouse gas emissions.
2. Classify the main technologies for CO_2 and CH_4 conversion.
3. Assess the environmental performance of each method using MCDA-LCA indicators.
4. Evaluate the correspondence of the greenhouse gases conversion methods to the principles of green chemistry.
5. Conduct experimental photocatalytic conversion of CO_2 and evaluate its environmental performance.
6. Recommend optimal solutions for sustainable industrial conversion.

Object of research is the process of: the process of greenhouse gas conversion using environmentally sustainable technologies.

Subject of research: environmental and chemical aspects of greenhouse gas utilization methods with an emphasis on photocatalysis and their compliance with the principles of green chemistry.

Methods of research:

1. Comparative analysis;
2. Multi-criteria analysis (MCDA-LCA)
3. Lab experiment (photocatalytic conversion);
4. Analytical modeling of process efficiency.

Personal contribution of the graduate: As a graduate student, I have conducted a laboratory experiment on the photocatalytic conversion of CO_2 using TiO_2-based catalysts and solar simulation, performed an independent evaluation of five leading methods for greenhouse gas conversion, and adapted the MCDA-LCA matrix for environmental performance rating. Original comparison tables and a structured interpretation of compliance with green chemistry principles were also developed.

Approbation of results:

1. The results of the study were presented to the commission of the Łódź University of Technology, Poland, where experimental work was carried out under the Erasmus+ program.
2. The results of the study were presented at the BUP Student Conference in Kaunas, Lithuania, from May 9, 2023, to May 12, 2023.

Publication:

1. Шестопал А.С., Радомська М.М. Аналіз відповідності методів очищення атмосферного повітря принципам сталого розвитку : *Сталий розвиток: захист навколишнього середовища. Енергоощадність. Збалансоване природокористування*. : матер. Х Міжнар. молодіж. конгресу (м. Львів, 27-28 березня 2025 р.). Київ : Яроче́нко Я. В. С. 79–80.
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4. Radomska M.M, Shestopal A.S The role of catalytic processes in enhancing the environmental safety of the chemical industry: тези доп. XXV міжнар. наук.-практ. конф. “Екологія, охорона навколишнього середовища та збалансоване природо-користування: освіта – наука – виробництво – 2023” (Харків, 27-28 квітня, 2023). Харків, 2023. С. 52-53.

5. Шестопал А.С., Радомська М.М. Аналіз відповідності методів очищення атмосферного повітря принципам сталого розвитку : *Сталий розвиток: захист навколишнього середовища. Енергоощадність. Збалансоване природокористування*. : матер. X Міжнар. молодіж. конгресу (м. Львів, 27-28 березня 2025 р.). Київ : Ярочéнко Я. В. С. 79–80.

CHAPTER 1

THE PROBLEM OF GREENHOUSE GASES IN THE ATMOSPHERE

1.1. Determining the impact of greenhouse gases on the climate change

It is well known that greenhouse gas emissions cause global imbalance in the biosphere and seriously harm the environment, despite international efforts to reduce them. In this context, significant scientific efforts are being made in several areas:

1) determining permissible greenhouse gas emissions;

2) developing methods for removing carbon compounds from the atmosphere;

3) searching for effective methods and developing technologies for converting these gases into valuable materials, such as synthesis gas, carbon materials and others.

To control emissions at the global level, the Kyoto Protocol was adopted, which is a key international document in the fight against climate change and complements the UN Framework Convention on Climate Change (UNFCCC). Its main objective is to stabilise greenhouse gas concentrations in the atmosphere at a level that prevents dangerous anthropogenic interference with the climate system [1].

The Protocol was adopted in 1997 in Kyoto (Japan) and entered into force on 16 February 2005 after ratification by a sufficient number of countries. The main objective of the Kyoto Protocol is to establish quantitative commitments for developed countries and countries with economies in transition to reduce or limit emissions of six major greenhouse gases. According to the Protocol, these countries were to reduce their total emissions by 5% from 1990 levels between 2008 and 2012 [2]. To achieve these goals, the Kyoto Protocol provides for the use of three flexible mechanisms:

1. Joint Implementation (JI). This mechanism allows countries that have made commitments to invest in emission reduction projects in other countries with similar commitments and count the reductions achieved towards their national targets.

2. Clean Development Mechanism (CDM). This mechanism allows developed countries to implement emission reduction projects in developing countries and receive credits for the reductions, which can be used to meet their commitments.

3. International Emissions Trading (IET). This mechanism allows greenhouse gas emission allowances to be traded, contributing to the cost-effective achievement of overall emission reduction targets.

Ukraine, having ratified the Kyoto Protocol in 2004, committed itself not to exceed the level of greenhouse gas emissions established in 1990. Thanks to the economic downturn in the 1990s, actual emissions in Ukraine fell significantly, allowing the country to actively use the Protocol's mechanisms, in particular the Joint Implementation mechanism. During the Protocol's period of validity, more than 270 projects were implemented in Ukraine, attracting significant investment and contributing to industrial modernisation.

The Kyoto Protocol has thus been an important step in international efforts to combat climate change, establishing legal commitments for countries to reduce greenhouse gas emissions and introducing mechanisms to facilitate the cost-effective achievement of these goals. Although existing technologies for reducing greenhouse gas emissions are important, their implementation often faces economic and technical barriers. Therefore, research and improvement of methods for capturing and converting greenhouse gases could be an important alternative in the context of a global strategy to combat climate change.

Greenhouse gases are atmospheric gaseous compounds that can absorb and emit infrared radiation, causing heat to be retained in the lower layers of the atmosphere and creating the greenhouse effect. The greenhouse effect is a natural phenomenon in which some of the infrared radiation emitted from the Earth's surface does not leave the atmosphere but is retained in it due to the presence of certain gases. It is thanks to this mechanism that the average annual temperature on the Earth's surface is maintained at around +15 °C. Without this effect, the temperature would be around −21 °C, which would make conditions on Earth unsuitable for life [3].

The natural greenhouse effect is caused by the presence of a number of gases in the atmosphere that are produced by natural processes. The most important greenhouse gases are:

1. Water vapour (H_2O) is the most abundant in terms of volume.
2. Carbon dioxide (CO_2) is produced by respiration, volcanic eruptions, etc.
3. Methane (CH_4) is the result of anaerobic decomposition of organic matter, especially in swamps and in the stomachs of ruminants.
4. Nitrous oxide (N_2O) is a product of nitrification and denitrification processes in the soil.
5. Ozone (O_3) also plays a role in protecting against ultraviolet radiation.

These substances are formed as a result of natural processes such as volcanic eruptions, water evaporation, biochemical reactions in the soil, the activity of microorganisms, etc.

Human activities lead to an increase in the amount of natural greenhouse gases above normal levels and introduce additional components that were not previously present in the atmosphere. The main sources of anthropogenic greenhouse gases are:

1. The combustion of fossil fuels (coal, oil, natural gas) in the energy sector and the transport sector deforestation, which naturally absorbs CO_2 from the atmosphere.
2. Agriculture, especially livestock farming, which produces large amounts of methane.
3. The decomposition of organic waste in landfills, which also contributes to CH_4 emissions.
4. Use of mineral nitrogen fertilisers, which increase N_2O emissions.

As a result, the concentration of carbon dioxide in the atmosphere has risen from around 280 ppm (parts per million) at the beginning of the industrial era to over 415 ppm today. This leads to an increase in global temperatures, causing climate change [4]. Although the natural greenhouse effect is essential for climate stability, the human-induced amplification of this effect poses a threat to ecosystems, human health and the functioning of planetary systems. It is also important to note that human-made greenhouse gases often have a greater ability to trap heat and thus contribute to global warming (*Table 1.1*).

Table 1.1

The main greenhouse gases that contribute to global warming

Greenhouse gas	Chemical formula	Global warming potential
Carbon dioxide	CO_2	1
Methane	CH_4	21
Nitrous oxide	N_2O	310
Hydrofluorocarbons (HFCs)		
HFC-23	CH_2F_2	11700
HFC-32	CH_2F_2	650
HFC-41	CH_3F	150
HFC-43-10mee	$C_5H_2F_{10}$	1300
HFC-125	C_2HF_5	2800
HFC-134	$C_2H_2F_4$ (CHF_2CHF_2)	1000
HFC-134a	$C_2H_2F_4$ (CH_2FCF_3)	1300
HFC-152a	$C_2H_4F_2$ (CH_3CHF_2)	140
HFC-143	$C_2H_3F_3$ (CHF_2CHF_2)	300
HFC-143a	$C_2H_3F_3$ (CF_3CH_3)	3800

HFC-227ea	$C_3H_7F_7$	2900
HFC-236fa	$C_3H_2F_6$	6300
HFC-245ca	$C_3H_3F_5$	560
Perfluorocarbons (PFCs)		
Perfluoromethane	CF_4	6500
Perfluoroethane	C_2F_6	9200
Perfluoropropane	C_3F_8	7000
Perfluorobutane	C_4F_{10}	7000
Perfluorocyclobutane	$c\text{-}C_4F_8$	8700
Perfluoropentane	C_5F_{12}	7500
Perfluorohexane	C_6F_{14}	7400
Sulfur hexafluoride	SF_6	23900

To estimate greenhouse gas emission volumes or emission allowance volumes, metric tonnes of CO_2 equivalent emission reductions are used, multiplied by the corresponding global warming potential. This allows the actual impact of emissions of certain volumes of greenhouse gases to be taken into account. Thus, among the main greenhouse gases that cause the greenhouse effect, not only carbon dioxide and methane attract particular attention, but also the so-called minor gases – nitrous oxide (N_2O), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs). Despite their relatively low concentration in the atmosphere, these substances have an extremely high global warming potential and a long atmospheric lifetime. Due to their anthropogenic origin and resistance to decomposition, they play a significant role in climate change, and their control is an important part of international climate policy.

Nitrous oxide is the third most important greenhouse gas after CO_2 and CH_4. Its global warming potential (GWP) is 310, which means that it traps heat in the atmosphere 310 times more effectively than carbon dioxide. The main sources of N_2O emissions are agriculture (especially the use of nitrogen fertilisers), industrial processes and biomass combustion. Between 1990 and 2013, nitrogen oxide emissions in Ukraine decreased by 40.2% [5].

Chlorofluorocarbons are synthetic greenhouse gases used mainly as refrigerants in refrigeration and air conditioning equipment and in the production of foam materials. Their GWP ranges from 140 to 11,700, depending on the specific compound. Although HFCs do not deplete the ozone layer like their predecessors (chlorofluorocarbons), they have a significant impact on climate change due to their high GWP.

Perfluorocarbons are another group of synthetic greenhouse gases that are mainly formed as by-products in the production of aluminium and semiconductors. They have an extremely high GWP, ranging from 6,500 to 9,200. PFCs are very stable in the atmosphere, with a long half-life, which makes them particularly dangerous for the climate. Reducing emissions of these substances is an important step in the fight against global warming, as their impact on the atmosphere significantly exceeds that of many traditional sources of greenhouse gases.

1.1.1 Carbon dioxide

The main gas responsible for most anthropogenic warming is carbon dioxide. It has a major impact due to its long lifetime in the atmosphere and its ability to absorb infrared radiation. Over the last hundred years, the concentration of CO_2 in the atmosphere has increased by 50% and reached over 420 parts per million (ppm), which is the highest value recorded in the last 800,000 years [6].

The sources of CO_2 that reach the atmosphere are divided into natural and anthropogenic. Natural sources include volcanic eruptions, the oxidation process of the environment caused by plants, the decomposition of organic matter, and rock erosion. Anthropogenic factors contributing to carbon dioxide emissions include the burning of fossil fuels (oil, coal, natural gas) and industrial processes. For example, the production of cement or steel in factories. In particular, deforestation and certain types of agricultural activities. Carbon dioxide reaches the atmosphere mainly through the burning of fossil fuels, industrial processes, and natural sources. The cycle of this greenhouse gas is as follows: through photosynthesis, plants absorb carbon dioxide (CO_2) from the atmosphere and, through oxidation, decomposition, and combustion, this gas is returned to the atmosphere.

1.1.2 Methane

Although methane occurs less frequently in the atmosphere than CO_2, it is a much more powerful greenhouse gas. Its global warming potential is 25 times greater than that of CO_2 per unit of mass over a 100-year period. According to the Intergovernmental Panel on Climate Change (IPCC), since the beginning of the industrial era, the concentration of methane in the atmosphere has increased by more than 150%.

Natural sources of methane in the atmosphere include methane eruptions, degassing of wetlands, and termite activity [7]. The main anthropogenic sources are natural gas extraction and transportation. At the same time, the leading factor is the agricultural sector, in particular livestock farming, during which methane is released as a result of digestion in ruminants. An additional and difficult source to quantify is the decomposition of organic waste in solid waste landfills with the release of CH_4.

In the atmosphere, methane (CH_4) undergoes chemical transformations: it enters into photochemical reactions, mainly with ozone, and is eventually converted into carbon dioxide (CO_2) and water vapor. Both products are greenhouse gases and participate in the global carbon cycle. Table 1.2 presents a comparison of the characteristics of two key greenhouse gases: carbon dioxide and methane, which are the main focus of this study.

Table 1.2

Comparison table of carbon dioxide and methane

Characteristic	Greenhouse gases	
	Methane	Carbon dioxide
Description	It has a high greenhouse effect potential per unit of mass. The concentration of methane in the atmosphere is lower than that of CO2. However, its impact on the heat balance is significantly higher.	The main gas causing global warming. Due to its significant volume and long presence in the atmosphere, it absorbs the most heat.
Sources of emission	Natural:methane source eruptions, bog degassing, anaerobic decomposition of organic matter. Anthropogenic: natural gas production and transportation, agriculture, landfills.	Natural: volcanic eruptions, respiration, aerobic decomposition of organic matter. Anthropogenic: burning fossil fuels, oil refining, deforestation, agriculture.
Formation process	Formed under anaerobic conditions	Formed as a result of combustion and oxidation.
Functioning in atmosphere	It interacts with ozone in the atmosphere and turns into carbon dioxide. Oxidation also leads to the formation of water vapor, which also contributes to the greenhouse effect.	It is absorbed by the ocean and also by plants during photosynthesis; decomposition of organic matter, oxidation, and combustion release CO2 into the atmosphere elements of the carbon cycle in the biosphere.

1.2. Natural methods of regulating the composition of the atmosphere and greenhouse gas content

Natural mechanisms regulating atmospheric composition and greenhouse gas concentrations play a key role in maintaining the planet's climate balance [8]. These include physical, chemical, and biological processes that interact with each other and ensure the stability of the atmospheric environment.

Among the main natural processes that control the content of carbon dioxide (CO_2) in the atmosphere are:

1. *Photosynthesis* is a biochemical process in which autotrophic organisms (green plants, algae, photosynthetic bacteria) use solar energy to convert carbon dioxide (CO_2) and water (H_2O) into organic compounds with the release of molecular oxygen (O_2). This mechanism is one of the leading ways of removing CO_2 from the atmosphere. Every year, terrestrial and aquatic vegetation absorbs approximately 120 billion tons of CO_2, contributing to the reduction of the greenhouse effect.

2. *CO_2 absorption by the world's oceans* involves both physical mechanisms of carbon dioxide dissolution in water and biological processes, such as phytoplankton photosynthesis. Ocean waters accumulate about one-third of global anthropogenic CO_2 emissions. At the same time, rising sea temperatures and ocean acidification can reduce the effectiveness of this absorption mechanism [9].

3. *Carbonate mineralization* is a geochemical process in which carbon dioxide reacts with minerals in the Earth's crust to form stable carbonate compounds. For example, the formation of calcite ($CaCO_3$) is part of a long-term natural carbon cycle that helps reduce CO_2 concentrations in the atmosphere over geological time scales [10].

4. *Biotic processes in the soil environment* also influence the regulation of carbon dioxide content. Microorganisms in the soil decompose organic matter, which can lead to both the release of CO_2 and the formation of stable organic compounds (humus), which, on the contrary, fix carbon. Depending on the type of soil, climatic conditions, and level of biological activity, these processes can have different effects on the carbon balance.

The regulation of methane (CH_4) content is also closely linked to biological mechanisms. In swamps, peat bogs, and other anaerobic environments, methane is produced by the microbiological decomposition of organic residues. In the atmosphere, methane is oxidized by photochemical reactions involving ozone and hydroxyl radicals (OH), resulting in the formation of CO_2 and water vapor, both of which contribute to the greenhouse effect. Although molecular nitrogen (N_2) is not a greenhouse gas, it participates in processes that lead to the formation of greenhouse compounds such as nitrous oxide (N_2O). In particular, the microbiological reactions of nitrification and denitrification in soils cause the transformation of nitrogen compounds, resulting in the formation of nitrogen oxides (NO_x), which have significant greenhouse potential.

The complex nature of natural regulatory mechanisms not only reduces the greenhouse effect but also maintains the functioning of ecosystems. For example, ocean phytoplankton not only absorbs CO_2, but also serves as a key link in food chains, regulates the organic carbon content in marine ecosystems, and influences climatic conditions. These natural mechanisms occur on a global scale and can be scaled up without significant additional costs. Systems such as forests and ocean ecosystems have significant potential to absorb carbon dioxide, which can be used to partially offset anthropogenic emissions. In the context of rising CO_2 and CH_4 emissions caused by human activity, natural regulatory mechanisms not only help stabilize the atmosphere, but also provide a range of related ecosystem services: biodiversity conservation, water purification, plant pollination, control of soil erosion processes, etc., particularly in the agricultural sector.

However, given the rapid increase in concentrations of greenhouse gases produced by humans, natural regulatory processes are proving insufficient to effectively curb climate change. The 2015 Paris Climate Agreement set a goal of limiting the increase in global average temperature to no more than 1.5°C above pre-industrial levels [11]. However, current trends in energy, urbanization, and political governance are jeopardizing this goal. Therefore, there is an urgent need to develop artificial technologies or enhance natural processes that promote the removal of greenhouse gases from the atmosphere and their long-term sequestration in stable forms of storage.

1.3. Conclusions to Chapter 1

Thus, this chapter analyzed the nature and mechanisms of the impact of major greenhouse gases on the climate system, examined their sources, extent of distribution, and the main international approaches to regulating emissions. It was determined that current natural absorption mechanisms are unable to compensate for the rapid growth of anthropogenic emissions, which necessitates technological intervention.

Against the backdrop of identified environmental risks and the limited self-cleaning capacity of the atmosphere, it is becoming increasingly important to find and implement engineering solutions aimed at removing and converting greenhouse gases. In this regard, the next section will provide an overview of modern methods for greenhouse gas utilization, including both removal technologies and approaches to the further use or storage of carbon compounds. This will allow for a comprehensive assessment of their effectiveness and environmental feasibility in the context of sustainable development.

CHAPTER 2
GREENHOUSE GASES UTILIZATION

2.1 Goals and methods of greenhouse gas disposal

Greenhouse gas disposal encompasses a range of technological, chemical, physical, and biological processes aimed at reducing the concentration of key greenhouse compounds in the atmosphere, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other gases which significantly contribute to the greenhouse effect and global climate change. The main task of utilization is to remove these substances directly from the atmosphere or from emission sources, convert them into less harmful or useful forms, and store them for long periods of time [12].

The main stages of utilization include: capturing greenhouse gases from industrial or biogenic sources; sorption or absorption using specialized materials or biological agents; conversion of captured substances into products of practical value (e.g., fuel or fertilizers) and stabilization of carbon compounds through geological sequestration or chemical binding.

The introduction of utilization solutions can significantly reduce anthropogenic pressure on the climate system, slow down global warming, and reduce the risks associated with extreme climate events, rising sea levels, and the degradation of natural ecosystems. At the same time, utilization opens up prospects for the sustainable use of resources and the development of economic models focused on environmental safety and the “green” transformation of industry. The functional model of utilization includes the following key stages: capture, conversion, and long-term storage of carbon compounds. Among the most promising methods are chemical binding of CO_2, geological storage, biological carbon fixation, and technologies for converting methane into liquid fuels or electricity. This contributes to stabilizing the carbon mass balance in the atmosphere and reducing overall climate risk [13]. A separate area is the utilization of biogenic gases, in particular from solid waste landfills, sewage treatment plants, and livestock infrastructure facilities. The use of such technologies reduces unintentional emissions of CH_4, a greenhouse gas with a global warming potential 25–28 times greater than CO_2. In addition, the biogas extracted can be used as an energy source, forming an integrated approach to waste management and energy-efficient production [14]. The use of recycling solutions reduces the risks of environmental imbalance, helps to preserve the functionality of climate control mechanisms, and promotes the formation of waste-free closed production cycles. In engineering practice, recycling serves to improve resource efficiency, reduce dependence on fossil fuels, and optimize carbon flows.

2.2. Removal of greenhouse gases

There are a number of approaches to greenhouse gas removal, the choice of which depends on the nature of the emission source and the stage of the process at which the removal takes place. Removal can take place either before or after fuel combustion, with subsequent utilization or safe storage of the removed substances.

2.2.1. Removal of greenhouse gases prior to combustion

Pre-combustion capture is based on the pre-treatment of carbon-containing raw materials, which involves the decomposition of fuel to form a gas mixture containing CO_2 and H_2. This approach is implemented through the following processes:

Gasification of solid fuels (coal, biomass) shows in Formula 2.1.

$$\square + \square_2\square \rightarrow \square\square + \square_2 \tag{2.1}$$

Reforming of natural gas (methane) shows in Formula 2.2.

$$\square\square_4 + \square_2\square \rightarrow \square\square + 3\square_2 \quad (2.2)$$

Water-gas shift reaction shows in Formula 2.3.

$$\square\square + \square_2\square \rightleftharpoons \square\square_2 + \square_2 \quad (2.3)$$

The main goal is to convert carbon into CO_2, which is easily separated from the gas mixture, and hydrogen, which can be used as an environmentally friendly fuel (Fig 2.1), [13].

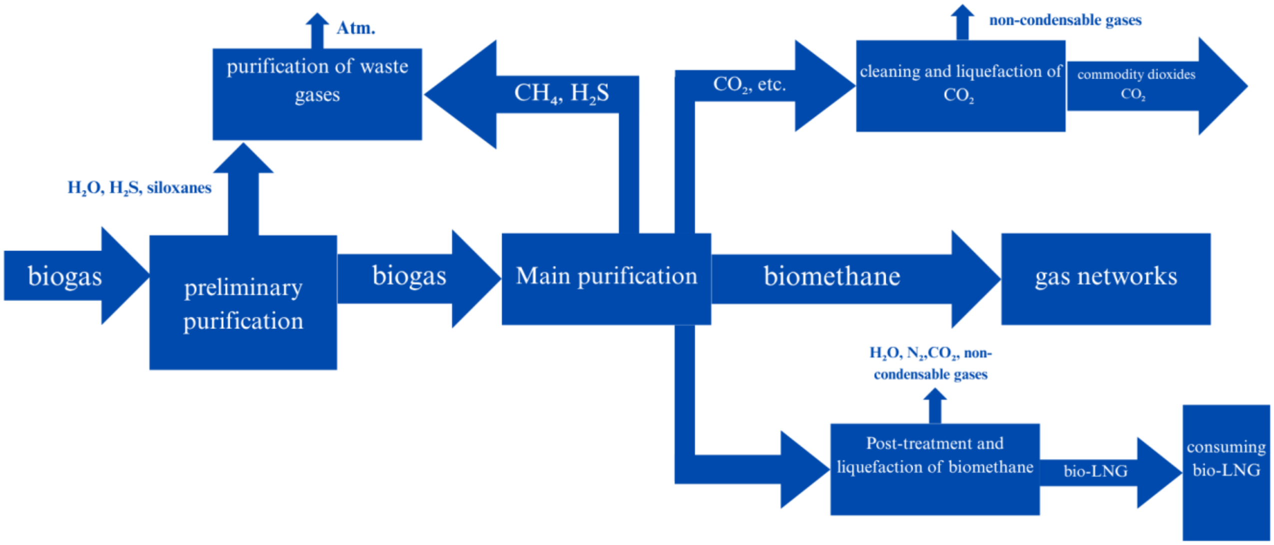

Fig. 2.1. Processes of greenhouse gas removal before and after

2.2.2 Post-combustion capture

Post-combustion capture involves removing carbon dioxide (CO_2) directly from the flue gases produced after the combustion of carbon-containing fuels. The concentration of CO_2 in such gases is usually 10–15%, along with nitrogen (N_2), oxygen (O_2), water vapor (H_2O), and other by-products.

The main method of CO_2 removal is absorption in aqueous solutions of amines, in particular monoethanolamine (MEA). This involves a chemical reaction between CO_2 and amino groups in Formula 2.4.

$$\square\square 2 + 2\square\square\square 2 \rightleftharpoons \square\square\square 3 + \; + \square\square\square\square\square\square - \qquad (2.4)$$

Thermal regeneration is used to regenerate the absorbent and separate pure CO_2 shown in Formula 2.5.

$$\square\square 2 + 2\square\square\square 2 \rightleftharpoons \square\square\square 3 + \; + \square\square\square\square\square\square -$$

(2.5)

In addition to absorption systems, other technologies are also used, in particular adsorption on solid sorbents (e.g., zeolites, activated carbon) and membrane separation, which is based on the selective diffusion of CO_2 through semipermeable membrane [15].

Various catalysts are used in these systems, including [16]:

1. Transition metal oxides. To this group includes copper (CuO), nickel (NiO), iron (Fe_2O_3), manganese (MnO_2). They demonstrate high efficiency in oxidation-reduction reactions aimed at flue gas purification.
2. Noble metals, like platinum (Pt), palladium (Pd), rhodium (Rh) are characterized by high catalytic activity, thermal stability, and long-term stability at high temperatures.

3. Zirconium dioxide (ZrO_2) catalysts, which are widely used as carriers of active substances due to their good thermal properties and promotion of uniform distribution of active catalytic phases.

The advantages of post-combustion capture include the possibility of its integration into existing thermal power plant (TPP) infrastructure and industrial facilities without the need for significant reconstruction of the technological cycle. At the same time, the low concentration of CO_2 in flue gases results in high energy consumption for removal: in particular, the energy consumption for regenerating the absorbent can account for up to 20–30% of the total energy produced by the plant.

The presence of impurities in flue gases requires the use of multi-stage purification systems, which complicates the overall implementation of the technology. In general, both pre- and post-combustion CO_2 capture methods have technical advantages and limitations related to energy consumption, adaptability to industrial conditions, and further possibilities for utilization or storage of carbon compounds (Table 2.1). The choice of method is determined by technical and economic feasibility, the nature of the emission source, and requirements for further use or storage of carbon [17].

Table 2.1

Comparative analysis of greenhouse gas removal methods

Parameter	Pre-combustion capture	Post-combustion capture
CO_2 concentration in gas mixture	High (20–40%)	Low (10–15%)
Technological complexity	High	Medium
Energy consumption	Moderate	High (20–30% of total energy expenditure)
Need for capital investment	Very high	Moderate
Adaptability to existing facilities	Limited	High
CO_2 capture efficiency	Up to 90–95%	70–85%
By-products	Hydrogen (clean fuel)	Regenerated absorbents require disposal
Catalysts used	Transition metal oxides (NiO, CoO), Pt, Rh	Metal oxides (CuO, Fe_2O_3, MnO_2), platinum group metals
Reaction temperature range	500–800 °C	100–350 °C (absorption); up to 500–600 °C (oxidation of residues)

2.3 Areas of utilisation

Greenhouse gas (GHG) disposal encompasses a set of technological and environmental measures aimed at reducing their concentration in the atmosphere through fixation (burial) or conversion through biological and technological processes (conversion) [18].

Fixation methods include geological storage, which involves removing CO_2 from industrial streams and injecting it into underground formations, such as depleted oil and gas fields or deep salt formations. The large volume of sedimentary basins indicates the potential of this method as an effective means of limiting GHG emissions. An additional method of carbon capture is the cultivation of biomass with subsequent burial, which allows CO_2 to be fixed through photosynthesis and removed from the global cycle. However, more promising approach is considered to be the conversion of greenhouse gases, which combines utilization with the production of useful products or energy. This approach is resource-efficient and economically viable. Conversion technologies enable CO_2 to be converted into carbon nanomaterials, synthesis gas, and other products using biological, electrochemical, photochemical, and thermochemical methods, thereby reducing dependence on fossil resources [19].

The choice of a specific disposal technology is determined by the type of emission source, technical and economic parameters, and the level of available technologies. Further development in this area depends on the implementation of innovative solutions aimed at improving the efficiency of GHG capture and processing. For comparison, five of the most common and environmentally sound disposal methods were selected, which combine emission reduction with the formation of secondary resources in accordance with the principles of the circular economy and sustainable development:

1. Thermochemical conversion of methane. High-temperature conversion of CH_4 into synthesis gas, which is then used in the production of fuel and chemical products. This method reduces emissions of methane, one of the most potent GHGs.
2. Chemical conversion of CO_2 and CH_4. Catalytic conversion of GHGs into synthesis gas and carbon nanostructures. This process not only reduces emissions but also creates added value through the production of useful substances.

3. Biological utilization is the use of microalgae for photosynthetic CO_2 absorption with the formation of biomass. The method is suitable for integration into emission control and biofuel production systems.

4. Direct Air Capture (DAC) means the use of chemical absorbents or filter materials to capture CO_2 directly from the atmosphere. The resulting gas can be stored or used in industrial processes.

Each method has specific environmental and economic characteristics that determine its suitability for use in specific conditions. A detailed assessment of these methods is provided in the following section.

2.3.1 Thermochemical conversion of methane

Methane undergoes thermochemical transformation at temperatures of 700–1200 °C with or without the use of catalysts, causing it to decompose into carbon and hydrogen. This process is also known as methane pyrolysis [20].

The main reaction of thermal decomposition shown in Formula 2.6:

$$\square\square_4 \rightarrow \square \rightarrow \square + 2\square_2$$

(2.6)

Key stages of the process of thermochemical conversion:

1. Methane is fed into the reaction zone, mostly in a gaseous state. The source of methane can be natural gas, biogas, or synthesis gas.

2. The reactor is heated to high temperatures (900–1200 °C). Heat source: electric heaters or partial combustion of methane.

3. In non-catalytic pyrolysis, the process is driven by high temperatures. Catalysts (Ni, Fe, Co) are used for catalytic pyrolysis, which allows the reaction temperature to be reduced to 700–900 °C.

4. Reaction products: hydrogen (H_2), which is collected in the gas phase, and carbon (C), which precipitates in a solid state in the form of nanotubes, graphite, or soot. After that, hydrogen is purified from impurities (CO, CH_4) to a purity level of over 99%.

The hydrogen obtained is used in hydrogen energy, ammonia production, and fuel cells. Solid carbon is used in the production of batteries, tires, electrodes, etc. Hydrogen yield efficiency can reach 50% of the methane mass. Thermal efficiency is 60–80% depending on the process conditions and catalysts [21]. The process is characterized by high environmental efficiency: the direct decomposition of CH_4 is not accompanied by the formation of CO_2. Hydrogen and carbon have significant industrial value, and the process itself is adaptable to different sources of methane.

Main limitations include high energy cost, need for high-temperature reaction equipment and problems with long-term catalyst stability. A promising direction is the integration of pyrolysis with renewable energy sources and the expansion of the range of target products.

2.3.2 Chemical conversion of greenhouse gases

Chemical conversion involves the use of reagents and catalysed reactions to convert CO_2 and CH_4 into compounds of industrial value:

1. synthesis of fuels (e.g. methanol) from CO_2;
2. use of CO_2 as a component in the production of building materials (concrete blocks);
3. conversion of methane into hydrogen.

Despite significant environmental benefits, reducing harmful emissions and creating alternative energy sources is the large-scale application of chemical conversion is accompanied by high energy consumption and costs, which necessitates further research and process optimization [22].

2.3.3 Photocatalysis

Photocatalytic conversion is a method based on the reduction or oxidation of CO_2 and CH_4 under the action of light radiation with the participation of photosensitive semiconductor materials [23]. The catalyst is activated upon absorption of photons, initiating chemical reactions that lead to the formation of substances such as methanol, formaldehyde, hydrocarbons, or synthesis gas. The common reactions include reduction of CO_2 to CH_4 or CH_3OH by the Formula 2.7.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2OCO_2 + 3H_2 \rightarrow CH_3OH + H_2O \qquad (2.7)$$

The second reaction is photodissociation of CO_2 by Formula 2.8.

$$CO_2 \rightarrow CO + ½O_2 \qquad (2.8)$$

The third reaction is oxidation of CH_4 is shown in Formula 2.9.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad (2.9)$$

The process of photocatalysis includes:

1. Supplying CO_2 or CH_4 to the photoreactor;
2. Activating the photocatalyst with light (UV or visible);
3. Exciting electrons and forming electron-hole pairs;
4. Conducting redox reactions on the catalyst surface;
5. Collecting and separating the reaction products: CO, CH_4, CH_3OH, H_2.

The main photocatalyst is titanium dioxide (TiO_2, anatase), which is characterized by high stability and low toxicity. Its limitation activity only in the UV range is compensated by modification with metals (Cu, Fe, Pt, Ag), heterostructures (CdS, ZnO, WO_3, Cu_2O), or dye sensitization [24]. Photocatalytic conversion has a number of significant advantages, including the ability to carry out processes at low temperatures (between 25 and 120 °C), the absence of toxic by-products, the use of solar energy as a radiation source, and the reintroduction of CO_2 and CH_4 into production cycles. The reactions produce substances with high applied value: methanol (CH_3OH) as an alternative fuel and raw material for the chemical industry, methane (CH_4) for gas energy, carbon monoxide (CO) for the production of synthesis gas, and hydrogen (H_2) as an energy carrier in hydrogen technologies. Despite its environmental benefits and scientific potential, the widespread industrial application of photocatalysis is currently limited. The main barriers are the low efficiency of the process under natural lighting due to the narrow absorption spectrum of photocatalysts (less than 5% of solar radiation is in the UV range), the high recombination rate of electron-hole pairs, which reduces the quantum yield, and the high cost of noble metals used to modify catalysts in order to increase their activity.

An additional complexity is the scaling of the technology: in industrial conditions, it is difficult to ensure uniform irradiation of the photocatalyst, maintain a stable temperature regime, and effectively remove reaction products.

2.3.4 Biological conversion of carbon dioxide and use of microalgae for absorption

In the context of increasing climate challenges, biological conversion of carbon dioxide (CO_2) is considered a promising strategy for reducing greenhouse gas concentrations in the atmosphere. This process is based on the ability of certain groups of microorganisms to assimilate methane or CO_2 during metabolic activity [25]. In particular, methanogenic archaea carry out the biochemical reduction of CO_2 to methane (CH_4) using molecular hydrogen (H_2) in an anaerobic environment. The reaction is described by the equation in Formula 2.10.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \qquad (2.10)$$

In this process, CO_2 acts as an electron acceptor, while H_2 acts as a donor. Representatives of the genera Methanobacterium and Methanobrevibacter catalyze this reaction through a series of sequential steps, including the formation of formyl-, methylene-, and methyl-groups, which interact with coenzymes such as methanofuran (MF), tetrahydro-methano-pterin (H_4MPT), and coenzyme M (CoM). The final phase of the reaction is catalyzed by methyl-coenzyme M reductase with the participation of coenzyme F_{430}, resulting in the formation of methane (Fig. 2.2).

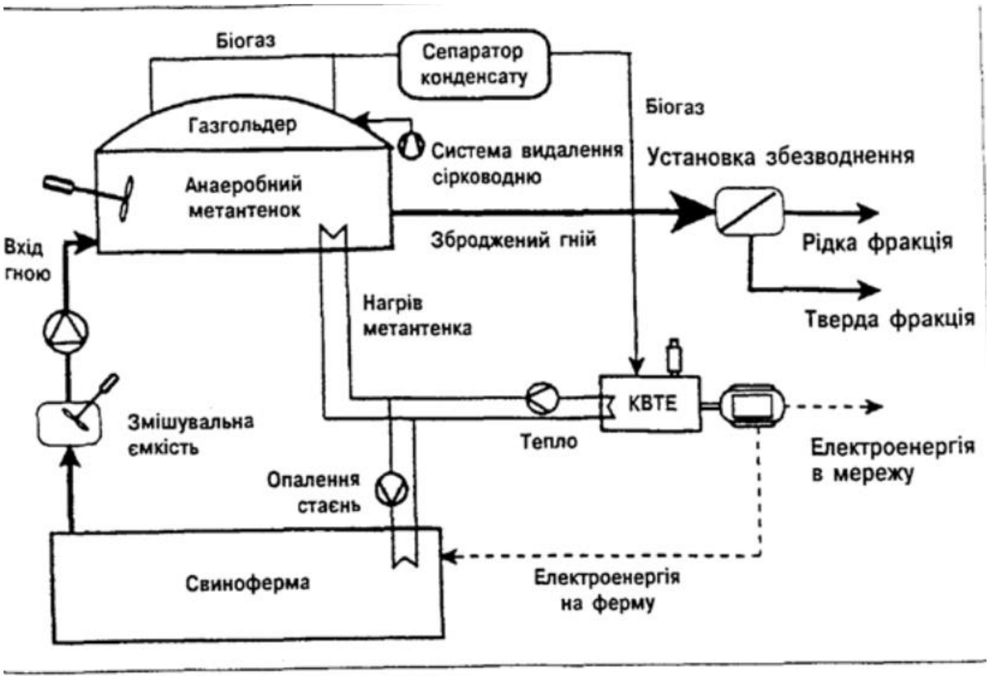

Fig. 2.2 Stages of CO_2 bioconversion under operating conditions.

The biological transformation of CO_2 has a number of environmental advantages. In particular, the processes occur at moderate temperatures and pressures, which significantly reduces energy consumption compared to traditional thermochemical methods. In addition, microorganisms can function in environments with impurities, which increases the stability of the processes to the quality of the input raw materials. The use of renewable hydrogen, for example, obtained by water electrolysis, allows the formation of closed carbon cycles. However, this approach is accompanied by a number of challenges, including low reaction rates and the need to maintain strict anaerobic conditions, which necessitates further research and technological optimization for large-scale implementation.

Despite these limitations, biological CO_2 conversion remains a promising method for reducing greenhouse gas emissions and obtaining renewable energy sources, which is in line with sustainable development strategies and environmental safety requirements.

The second option is the use of microalgae. These microorganisms, thanks to their ability to photosynthesize, effectively absorb CO_2 and convert it into biomass that can be used in various industries. The environmental significance of this method lies in its ability to combine greenhouse gas reduction with the creation of economically valuable products. Microalgae absorb CO_2 from the environment through photosynthesis. Under optimal conditions, one ton of algae can absorb approximately 1.8 tons of CO_2. This makes them one of the most effective biological tools for combating climate change. For maximum absorption, photobioreactors are used special systems that maintain optimal conditions for microalgae growth. In such systems, CO_2 concentrations can reach up to 10%, which is significantly higher than atmospheric levels (0.04%), and this accelerates the metabolism of algae.

The use of microalgae for CO_2 absorption has several important environmental advantages. First, it is a natural and sustainable way to dispose of greenhouse gases. Compared to man-made methods, which often require significant energy resources, microalgae-based systems are energy efficient. Second, microalgae cultivation can be integrated into industrial processes, such as power plants or chemical factories, where high concentrations of CO_2 can be fed directly into photobioreactors. Moreover, algae are capable of removing heavy metals and organic pollutants from water, making them useful for aquatic ecosystems. One hectare of microalgae can utilize up to 50 tons of CO_2 per year, which is equivalent to the average annual emissions of 10 cars.

The biomass obtained from microalgae has a wide range of applications, which enhances the economic viability of this technology. It is used to produce biodiesel, animal feed, fertilizers, as well as pharmaceutical and cosmetic products. For example, biodiesel from algae has a significantly lower carbon footprint than fossil fuels. According to research, one hectare of microalgae can produce up to 15 tons of biodiesel per year. The use of algae is also important for the urban environment. The development of vertical farms and building facades covered with photobioreactors allows CO_2 absorption to be integrated directly into the urban environment, reducing air pollution.

Despite its many advantages, microalgae technology faces some challenges. The main problems remain the high cost of equipment and the energy required to maintain optimal conditions in photobioreactors. At the same time, the development of new technologies, such as the use of solar energy for lighting or automated environmental control systems, is gradually reducing these costs. Microalgae are an environmentally effective tool for CO_2 absorption, combining the reduction of greenhouse gas concentrations with the production of useful products. With support for innovation and integration with existing technologies, this technique has the potential to become a key component in the fight against climate change. Microalgae demonstrate how nature can be our ally in creating a sustainable future.

2.3.5 Direct Air Capture of carbon dioxide

Direct Air Capture (DAC) is an innovative technology that allows CO_2 to be removed directly from the air, regardless of its source. This method is particularly important for combating accumulated greenhouse gas emissions and achieving zero-emission targets [26]. The DAC process consists of several key steps. First, atmospheric air is fed into a capture system using large fans. The CO_2 is then absorbed or adsorbed using chemical solutions, such as sodium hydroxide, or solid sorbents, such as amine materials. Once the sorbents are saturated, the CO_2 is released by heating or reducing the pressure, resulting in a concentrated stream of CO_2 for further use or storage.

Despite its promise, DAC technology faces certain challenges. In particular, due to the low concentration of CO_2 in the atmosphere (about 0.04%), the process requires significant energy consumption, which affects its economic efficiency. However, with the development of technology and the use of renewable energy sources, costs are expected to decrease and DAC is expected to be more widely implemented in the future. Direct CO_2 removal from the atmosphere is an important tool in the fight against climate change, especially for achieving net-zero emissions targets and offsetting historical greenhouse gas emissions.

2.4 Comparative assessment of greenhouse gas disposal methods

To compare greenhouse gas utilization methods in terms of technical and economic parameters, a number of key indicators were selected:

1. type and complexity of equipment;
2. necessary materials and reagents;
3. process duration;
4. processing cost;
5. technological limitations for implementation;
6. nature and value of the reaction products.

This approach not only allows for an objective assessment of each method in a specific industrial or environmental situation, but also reveals their feasibility in terms of their impact on the environment. Analysis based on these criteria makes it possible to identify the most effective and sustainable solutions that combine environmental safety, economic efficiency, and technical feasibility in the context of modern climate policy [27].

To express the advantages and environmental performance of the methods considered in the form of a quantitative assessment, an adapted MCDA-LCA (Multi-Criteria Decision Analysis and Life Cycle Assessment) scale was used, as recommended in the report of the European Commission's Joint Research Centre (2021) and supported by publications in Science of the Total Environment and Springer Environmental Management. Each method is rated from 1 to 10 on an integrated score based on:

1. global warming potential (GWP impact);
2. energy neutrality or compensability;
3. toxicological safety and absence of polluting residues;
4. possibility of product reuse;
5. potential for technological integration with other ecosystem processes.

When analyzing greenhouse gas disposal methods, it is also necessary to consider their compliance with the principles of green chemistry.

Green chemistry is an interdisciplinary field of chemical science that combines knowledge from organic chemistry, environmental technology, engineering, toxicology, and sustainable development. It emerged in response to the growing need to transform industrial production, which has long been based on the use of toxic, hazardous, and non-renewable substances. Unlike traditional chemistry, which often focused solely on obtaining the target product, green chemistry takes into account the entire life cycle of materials, from raw material extraction to final waste disposal. The goal of green chemistry is to reduce the environmental footprint of the chemical industry, ensure human and environmental safety, and minimize energy and resource consumption. The key to green chemistry is preventing pollution rather than dealing with its consequences. It is based on the idea that the best way to reduce risk is to avoid hazards at the design stage of molecules and processes.

Since the principles of green chemistry were formulated in 1998, there has been a significant rethinking of approaches to chemical synthesis, especially in areas related to climate protection and greenhouse gas emissions reduction (Fig. 2.3).

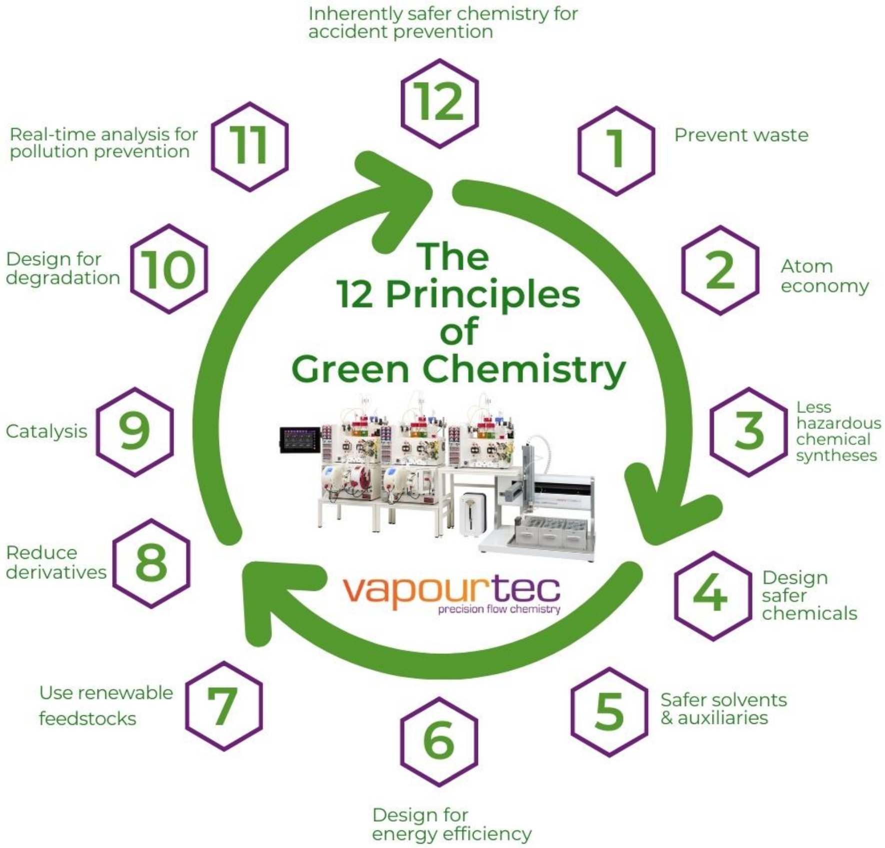

Fig. 2.3. Principles of “green chemistry’’

The environmental efficiency of greenhouse gas utilization processes must be inextricably linked to technological efficiency, provide for the rational use of valuable resources, and ensure the safety of all participants in the process.

2.5. Conclusions to Chapter 2

This chapter explored the main methods of greenhouse gas utilization using carbon dioxide as an example. It is shown that the most environmentally sound methods are those that ensure not only the removal of greenhouse gases, but also their conversion into stable, industrially valuable, or environmentally safe forms.

To select the optimal utilization method, a number of factors must be taken into account, including the nature of the reagents used, the energy balance of the process, and the industrial significance of the final reaction products. The next section of this work will be devoted to a comparative analysis.

CHAPTER 3

COMPARATIVE ANALYSIS OF EFFECTIVENESS OF GREENHOUSE GAS DISPOSAL METHODS

3.1. Results of comparing greenhouse gas disposal methods in terms of environmental effectiveness

Based on the selected criteria, a comparative table of greenhouse gas utilization methods was created (Table 3.1), which demonstrated the main advantages and disadvantages of the methods from a technical and economic point of view.

Table 3.1.

Comparative analysis of greenhouse gas utilization methods

Method	Equipment	Materials and Reagents	Time	Processing Cost	Application Limitations	Reaction Products
Thermochemical conversion of methane	High-temperature pyrolysis reactors, heating elements, cooling systems	Methane (natural gas, biogas), catalysts (Ni, Fe, Co), inert gases	30–120 min	High	Requirement for high temperatures, stable catalysts	Syngas (CO, H_2), carbon nanomaterials

Chemical conversion of greenhouse gases	Chemical reactors, gas feed systems, storage containers	CO_2, CH_4, catalysts (NiO, CuO), inert gases	Depends on reaction type	Medium (catalysts, equipment)	High temperature and pressure, safety control of reaction processes	Methanol, CO, syngas, nanostructured carbon
Photocatalytic conversion	Electrochemical cells, photoreactors or high-temperature reactors	CO_2, electrolytes, semiconductor photocatalysts, H_2	From several minutes to hours	High (expensive catalysts, energy consumption)	Scaling challenges, limited efficiency of photocatalysts	Methanol, carbon nanomaterials, CO, H_2
Use of microalgae	Photobioreactors, CO_2 and light supply systems, cultivation tanks	Microalgae, water, CO_2, mineral fertilizers	5–10 days	High (infrastructure, energy costs for lighting and circulation)	Requirement for stable conditions (light, temperature), high sensitivity to contamination	Biomass (for biofuel, fertilizers, feed), purified water
Direct Air Capture (DAC)	Fan systems, sorption towers, thermal regeneration units	Sodium hydroxide, amine sorbents (MEA), water	2–6 hours	Very high (sorbents, thermal energy, infrastructure)	High energy consumption, need for renewable energy sources for stable operation	Concentrated CO_2 (for storage or reuse)

Various methods of greenhouse gas conversion have the potential not only to reduce anthropogenic emissions but also to enable the transition to carbon-neutral or even climate-positive industrial solutions. Given the different nature of each process (physical-chemical, biochemical, or absorption-thermodynamic), it is important to evaluate methods according to unified criteria of environmental efficiency. This allows us to identify not only the immediate environmental benefits of implementing a technology, but also its long-term sustainability in an ecosystem context.

1) Thermochemical conversion of methane. The environmental contribution of this method is not limited to reducing CH_4 concentrations. Its important feature is the complete absence of nitrogen and sulfur oxides in the reaction system, which are typically undesirable by-products of traditional combustion. In addition, the processes of depositing solid carbon in technically valuable forms (graphene, carbon nanotubes) may in the future replace materials with a high carbon footprint, such as steel or concrete.

2) Chemical conversion of greenhouse gases. In addition to the formation of synthesis gas, the method is one of the few that provides a controlled transition between the gas and liquid phases with the formation of compounds that are susceptible to further catalysis or polymerization. This creates a basis for the development of technologies at the intersection of chemical recycling and the secondary resource cycle, for example, in the production of biopolymers. Importantly, within this method, CO_2 can act not only as a substrate but also as a regulator of reaction kinetics, potentially replacing harmful regulators in synthetic schemes.

3) CO_2 conversion (electro- and photocatalytic). The uniqueness of this approach lies in the fact that it allows the energy from an external source (e.g., sunlight or excess electricity) to be transformed into a chemically bound form with simultaneous capture of CO_2. Thus, the technology combines the functions of energy storage and emission reduction. It is also worth noting that photocatalytic processes can be localized in small reaction volumes, allowing them to be adapted to urban environments.

4) Biological conversion using microalgae. Scientific interest in this technology is growing due to the potential of algae to adapt to extreme environmental conditions: high CO_2 concentrations, elevated temperatures, and acidity. Thus, they can act as a means of phytoremediation of technologically altered ecotopes. Another advantage is the possibility of creating multifunctional systems: carbon capture and wastewater

treatment as well as heavy metal fixation, which proves the complexity of the environmental impact.

5) Direct CO_2 capture from the atmosphere (DAC). This technology is not only unique in its independence from point sources of emissions, but also opens up prospects for the creation of so-called mobile carbon capture modules. They can be moved to regions with critical CO_2 levels. For example, urbanized valleys or closed air basins, which expands the range of responses to local climate threats. Within the circular economy, DAC technology has the potential to work in conjunction with geomineral processes and the production of artificial fuels.

In terms of compliance with the principles of green chemistry, the methods considered can generally be said to be relatively effective:

1) Waste prevention. Industrial CO_2 capture systems use methods where all by-products are either converted into energy carriers or closed within the production cycle (e.g., in Power-to-X systems). This minimizes the need for further gas or water purification.

2) Atom savings. Technologies for converting CO_2 into methanol or formate are designed so that all CO_2 atoms and reactants (e.g., hydrogen) are incorporated into the target product, ensuring high atomic efficiency and minimal waste.

3) Less hazardous chemical synthesis. Reactors using photocatalysis or electrocatalysis avoid high temperatures, explosive conditions, or toxic reagents (e.g., conversion of CO_2 to synthesis gas without combustion as a safe alternative to conventional gas generators).

4) Design of safer chemical products. Methanol or synthetic fuels produced from CO_2 can be used in fuel cells without emissions of heavy metals or carcinogens, such products are being designed as safe alternatives to gasoline, diesel, or fuel oil.

5) Safer solvents and auxiliary substances. Instead of organic solvents, water is used in most processes or the liquid phase is eliminated altogether by converting the

process to a gas phase, which allows the technology to be easily integrated into wastewater treatment plants or CO_2 capture installations in factories.

6) Energy efficiency. Reactors powered by sunlight enable CO_2 utilization without additional electricity consumption, making them an ideal solution for regions with high solar potential.

7) Use of renewable raw materials. CO_2 from flue gases or the atmosphere, biogenic methane from organic waste are renewable raw material sources; in industry, they can be integrated into carbon capture and utilization (CCU) plants or biogas plants.

8) Reduction of derivatives. In photocatalytic or electrocatalytic conversion of CO_2, no additional modification of the gas is required before the reaction (no activation, functionalization, etc.), which reduces the number of steps and the need for chemical modifiers, facilitating scaling.

9) Catalysis. Industrial processes use heterogeneous catalysts, such as those based on TiO_2, Fe_2O_3, Cu-Zn, which can be reused thousands of times. This saves resources and makes the process continuous over time an important advantage for large volumes.

10) Design for degradation. CO_2 disposal products (methanol, acetic acid, formates) are either burned with minimal emissions or biodegraded, allowing them to be incorporated into bioeconomy cycles without creating toxic residues.

11) Real-time analysis to prevent contamination. Industrial photocatalysts use online CO, CH_4, and O_2 sensors to monitor reaction quality and safety. For example, NDIR (non-dispersive infrared spectroscopy) sensors are integrated into new-generation reactor systems.

12) Safe chemistry for accident prevention.CO_2 utilization in photochemical reactors reduces the risk of explosion, overheating, or contamination. This allows small modules to be built directly at emission sites, such as near power plants or cement factories, without endangering workers or the environment.

The utilization of CO_2 and CH_4, which are key greenhouse gases, requires not only technological efficiency but also environmental responsibility. That is why green chemistry has become the methodological basis for the development of innovative solutions in the field of emission reduction. Modern methods, such as photocatalysis, electrocatalysis, bioconversion, mineral carbonization, etc., have been developed and improved taking into account the principles of safety, energy efficiency, renewability, and minimization of harmful effects. According to the results of the assessment of the environmental efficiency of the methods studied (*Table 3.2*), photocatalysis and the use of microalgae are the most effective. The photocatalytic process, which has advantages in terms of technical and economic indicators, is considered in more detail below. Photocatalysis is considered one of the most promising methods for CO_2 utilization due to its environmental safety, energy efficiency, and the possibility of using renewable energy sources.

Table 3.2.

Comparative Table of Environmental Efficiency (MCDA-LCA)

Utilization Method	Rating (1–10)	Justification of Rating
Thermochemical conversion of methane	8	Does not produce volatile by-products, generates valuable solid carbon, suitable for material substitution
Chemical conversion of greenhouse gases	7	Reactions yield high-value products, possibility to regulate chemical activity via CO_2
Photocatalytic conversion	9	Combines CO_2 capture with renewable energy storage, low environmental impact
Microalgae for CO_2 absorption	10	Creation of dual-action biosystems (carbon capture and phytoremediation); stability under anthropogenic conditions

Direct Air Capture (DAC)	8	Capability for mobile response to local emissions; flexible integration into closed-loop infrastructure

3.2. Photocatalytic conversion of methane and carbon dioxide

This part of the chapter focuses on the photocatalytic conversion of methane (CH_4) and carbon dioxide (CO_2), which is one of the most promising methods for the environmentally friendly disposal of greenhouse gases. The chosen direction is multifunctional, as it allows not only to reduce GHG concentrations, but also to produce synthesis gas and carbon nanomaterials with high industrial potential. Despite the high energy consumption of photocatalytic systems on an industrial scale, they are considered a strategic component of a carbon-free economy.To comprehensively assess the environmental performance of photocatalysis, an experimental study of the dry reforming of methane was conducted, in which CO_2 and CH_4 are converted into synthesis gas and nanostructured carbon deposits.

The research was carried out at the Lodz University of Technology (Poland) from March 1 to May 25, 2023. The following steps were taken to conduct the experiment:

1. Analysis of literature data on dry reforming of methane, carbon deposition processes, and synthesis gas.
2. Synthesis of nickel, cobalt, iron, and aluminum-based catalysts by impregnation [28].
3. Physical and chemical characterization of the obtained catalysts using atomic adsorption spectroscopy, Brunauer-Emmet-Teller analysis, temperature-programmed desorption of NH_3 and CO_2, as well as temperature-programmed reduction.
4. Measurement of catalyst activity in the dry reforming of methane at temperatures of 500–800 °C.

5. Characterization of reaction products by gas chromatography with a thermal conductivity detector, total organic carbon analysis, thermoprogrammed oxidation, and X-ray diffraction.

The experiment is important for several reasons. First, it allows quantitative determination of the efficiency of greenhouse gas removal using heterogeneous catalysts under real temperature conditions. Second, analysis of the reaction products makes it possible to establish the relationship between synthesis gas and carbon fixation, which is critical for the environmental safety of the process. Third, the structured carbon materials formed can serve as a long-term form of carbon fixation and have industrial value as substitutes for materials with a high carbon footprint (Table 3.3).

Table 3.3

Types of carbon species formed at various temperatures

Carbon structure	Designation	t, °C
Adsorbed, atomic carbon	C_α	200-400
Amorphous and polymeric carbon	C_β	400-600
Graphite-like carbon	C_γ	500-800
Whiskers	C_v	300-1000

Thus, the experiment not only confirms the reactivity of the system but also demonstrates its environmental potential, from reducing emissions to producing secondary raw materials. The results provide grounds for considering photocatalytic conversion as part of a strategy for decarbonizing industrial emissions. The experiment used dry reforming of methane (DRM), where CO_2 acts not only as a harmful component but also as an active reagent. This opens up the possibility of using CO_2 as a secondary raw material, supporting the concept of a closed carbon cycle.

The process involved heterogeneous catalysts based on gamma-aluminum oxide (γ-Al_2O_3) activated with nickel, cobalt, and iron. The results showed that Ni and Co catalysts have the highest activity in DRM (Figure 3.1).

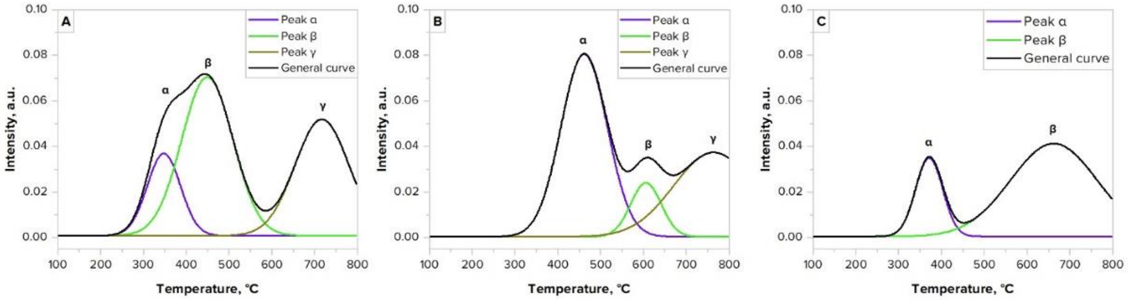

Fig. 3.1 Temperature-programmed reduction for Ni/γ-Al_2O_3 (A), Co/γ-Al_2O_3 (B), Fe/γ-Al_2O_3 (C)

This activity is explained by the low reduction temperature of oxides and the high dispersion of the active phase, which provides a greater number of active centers for reagent adsorption. Iron-based catalysts showed lower activity due to the formation of thermally stable spinel structures of the $FeAl_2O_4$ type, which have weak catalytic ability in DRM.The temperature stability of the process and high methane and CO_2 conversion rates (up to 99% on Ni and Co catalysts) indicate significant potential for industrial application.

The maximum synthesis gas yield with an H_2/CO ratio close to stoichiometric was also recorded, which is acceptable for further chemical transformations, in particular the synthesis of liquid fuels using the Fischer-Tropsch method. From an environmental point of view, photocatalytic DRM minimizes the formation of by-products characteristic of traditional combustion. The absence of nitrogen and sulfur oxides, as well as ash residues, allows this method to be considered virtually waste-free. At the same time, part of the carbon that could return to the atmosphere as CO_2 is fixed in the form of graphene-like and fibrous structures.

These materials are stable and have commercial value as components for the production of composites, electrodes, and adsorbents. The results of temperature-programmed oxidation (TPO) confirmed the high stability of carbon deposits and their inertness to oxidation at temperatures up to 550 °C, which indicates high structure and graphitization. X-ray diffraction (XRD) analysis revealed characteristic peaks at $2\theta \approx 26°$, which corresponds to the crystalline order of carbon.

Thus, Ni- and Co-catalysts based on γ-Al_2O_3 demonstrate high catalytic activity and environmental reliability, making them suitable for use in carbon-neutral or carbon-negative technologies. The photocatalytic conversion of CH_4 and CO_2 by high-temperature catalysis should be considered not only as a means of utilizing greenhouse gases, but also as a platform for the transition to a circular carbon economy. The application of this technology can not only reduce global warming potential (GWP) but also stabilize local emissions in industrial regions with high concentrations of CO_2 and CH_4 and the presence of anthropogenic heat sources. This ensures the flexibility and adaptability of the technology in the context of modern environmental regulations.

3.3 Analysis of the compliance of greenhouse gas disposal methods with the principles of green chemistry

In the context of the escalating climate crisis and rising concentrations of greenhouse gases, adherence to the principles of green chemistry in the development of new technologies becomes not only desirable but critically necessary. The application of the 12 principles of green chemistry, such as atom economy, avoidance of toxic substances, use of catalysis, and prevention of waste formation, enables the reduction of the negative environmental impact of production processes. This forms the basis for creating a closed carbon cycle, in which CO_2 emissions are converted into raw materials. Incorporating environmental criteria at the process design stage ensures not only efficiency but also safety, scalability, and economic viability of the technology.

3.3.1. Photocatalysis

The photocatalytic process relies on the complete utilization of CO_2 as a feedstock without generating toxic or persistent by-products. The reaction products include only the target substance and molecular oxygen. During photocatalytic CO_2 reduction, no pollutants are formed, eliminating the need for further purification or disposal of secondary waste, unlike many thermochemical methods. Additionally, photocatalytic systems do not require absorbers or chemical filters, thus removing potential sources of contamination at the design stage.

Photocatalytic processes are designed to integrate all atoms of the reactants (including carbon, hydrogen, and oxygen) into the final products. This is achieved through precise control of reaction conditions and the use of highly selective catalysts. For example, laboratory studies have demonstrated up to 93% atom efficiency in the photocatalytic conversion of CO_2 to formate. Simultaneously, the use of solar radiation as an energy source reduces energy consumption to less than 0.5 MWh per ton of product.

Using $Cu_2O/g\text{-}C_3N_4$ as a photocatalyst provides high CO_2 conversion to formate with atom efficiency exceeding 90%. This decreases the need for additional reagents or repeated purification and reduces the volume of starting materials, conserving resources in industrial settings. This principle is essential for lowering the carbon footprint of the entire process [29]. Photocatalysis avoids the use of aggressive reagents such as concentrated acids, bases, or organic solvents. Reactions occur either in aqueous media or gas phase without high temperatures, pressures, or explosive components.

For example, methanol synthesis from CO_2 proceeds at temperatures up to 40 °C in the presence of only light and a photocatalyst. This minimizes risks to production personnel and reduces safety-related expenses. Due to the absence of harmful substances, products require no neutralization, further reducing environmental burden. In terms of industrial safety, such lines can be certified as “low-hazard.” The primary energy source in photocatalysis is solar radiation or artificial UV/visible light, replacing heating or compression required by other methods. This results in significantly lower energy consumption compared to electrochemical or thermochemical systems. For instance, solar reactors coated with TiO_2 consume electricity only for gas circulation. This allows photocatalysis to be applied in decentralized units in areas where electricity is costly or unstable. The low energy threshold enables autonomous operation, and the use of renewable energy supports the transition to a carbon-neutral industry.

Photocatalytic processes utilize solid, stable catalysts that can be reused multiple times without loss of activity, fully complying with the 9th principle of green chemistry. For example, TiO_2 doped with silver or copper can operate in reactors for over 1000 hours without regeneration. This reduces catalyst replacement costs and minimizes the production of harmful by-products. Catalysis also achieves high selectivity, producing only the desired product (e.g., formate or methanol), reducing the need for subsequent separation and purification. Furthermore, photocatalysts are generally non-toxic, simplifying post-use handling. Currently, photocatalysis is beginning to be implemented on an industrial scale. Successful pilot projects at thermal power plants and cement factories in Japan and South Korea convert CO_2 emissions photocatalytically into methanol for reuse in the energy sector. Another project under testing in Germany (SOLAR2CHEM) and the UAE converts CO_2 into synthesis gas, subsequently used in Fischer-Tropsch synthesis for agricultural applications [30].

The recent introduction of mobile container modules enables local air purification near industrial sites or urban emission sources. For example, the startup Skytree developed mini-photocatalysts that convert CO_2 into ethanol in urban environments.

3.3.2 Thermochemical conversion of methane

Primarily, this process prevents waste formation by utilizing the entire methane molecule without producing CO_2, NO_x, or other toxic compounds. The reaction products hydrogen and carbon are suitable for direct use: hydrogen in fuel cells, transport, and industry; carbon in battery manufacturing, electrodes, and construction materials. Thus, all reaction components are commercially valuable, making the process nearly waste-free.

Thermochemical methane conversion (TMC) also achieves complete atom economy: one carbon atom converts into a solid phase, while four hydrogen atoms form molecular hydrogen. Atom efficiency using Cu/Ni catalytic systems reached 98.7%, an exceptionally high figure under industrial conditions. This minimizes raw material losses and ensures efficient methane utilization.

The process is also safe, as TMC does not require acids, bases, organic solvents, or other hazardous substances. Reactions occur in an inert gas environment, such as argon or nitrogen, or sometimes without gas, significantly reducing risks of toxic emissions, explosions, and equipment corrosion. Moreover, the synthesis does not involve washing or neutralization steps typical of other processes, making TMC safe for operators and the environment. Despite its high operating temperature (700–1200 °C), TMC can be powered by renewable energy sources. The SUN-to-LIQUID project in Europe investigates methane pyrolysis using solar heat concentration, replacing traditional electric or gas heating. Pilot plants achieve up to 80% energy efficiency with heat recovery or electric furnaces powered by green energy. Thus, TMC shows strong adaptability to a climate-neutral economy [31].

Catalysts significantly reduce reaction temperature and improve selectivity in TMC. For example, Ni/SiO_2 or Fe/Al_2O_3 catalysts enable methane decomposition at 750 °C instead of over 1000 °C without catalysts. Hydrogen yields reach 47–52% of methane mass, and catalyst lifetimes exceed 1000 hours without significant activity loss. Catalytic systems are reusable, aligning with the principle of resource efficiency. Industrial implementation of thermochemical methane conversion demonstrates tangible results globally. In the USA, Monolith Materials operates a pilot plant in Nebraska producing so-called turquoise hydrogen for ammonia synthesis and high-quality technical carbon for the tire industry. In Australia, Hazer Group is scaling iron-catalyzed methane pyrolysis, preparing a commercial plant with over 1000 tons of hydrogen per year by 2025. The European SUN-to-LIQUID project tests combining concentrated solar heat with TMC to produce synthesis gas used in Fischer–Tropsch synthesis for liquid fuel production.

In Switzerland, ETH Zurich researchers developed a laboratory setup for biogenic methane pyrolysis with over 95% hydrogen selectivity and graphite-like solid carbon formation [32].

Meanwhile, in Ukraine, research projects at the Institute of Physical Chemistry of the NASU explore local TMC applications at biogas plants, particularly at municipal solid waste landfills where CH_4 content consistently exceeds 45%.

In summary, thermochemical methane conversion combines high greenhouse gas utilization efficiency with the production of pure hydrogen and functional carbon materials. The method fully aligns with key green chemistry principles, including waste prevention, atom economy, and catalysis. Its practical application demonstrates technical and economic feasibility at both global and local scales. Considering its adaptability to renewable energy, TMC has the potential to become a core technology in industrial decarbonization strategies.

3.3.3 Chemical conversion of greenhouse gases

Firstly, this method complies with the principle of atom economy, according to which all atoms of the reactants should be incorporated into the final products. In processes such as dry methane reforming, only the target product is formed without harmful by-products. This means that all carbon atoms remain in circulation without losses as waste or side gases.

Moreover, chemical conversion implements the principle of catalysis, considered one of the key principles of green chemistry. Catalytic systems based on transition metals (Ni, Co, Cu) combined with supports such as Al_2O_3 or CeO_2 provide high reaction selectivity, enabling avoidance of side reactions and lowering the energy barrier.

In the context of practical application and validation, research conducted at Zurich University of Applied Sciences demonstrated that $Ni/CeO_2–Al_2O_3$ catalysts achieve over 85% selectivity at temperatures below 800 °C. Another achievement of chemical conversion is the avoidance of aggressive reagents and toxic solvents. In most implemented chemical conversion schemes, including electrochemical CO_2 reduction, chlorine-containing compounds, concentrated acids, or bases are not used.

This allowed the Power-to-X program in Germany to convert CO_2 into sodium formate without generating toxic residues. The reaction product is applied in the pharmaceutical and food industries. It is also important to highlight the principle of maximizing energy efficiency: during electrochemical conversion powered by electricity from solar panels or renewable energy sources, the system not only avoids consumption of fossil fuels but also enables storage of energy in chemical bonds. Thus, chemical CO_2 conversion becomes a technology with a dual environmental function: emission reduction and utilization of excess renewable energy [33].

Additionally, the advantage of selectivity over multicomponent product mixtures should be emphasized, as most reactions within this approach have a clearly defined target substance. For example, in photothermal chemical reactions employing copper catalysts, CO_2 conversion into formate reaches atom efficiency above 90%, indicating the completeness and specificity of the reaction. The implementation of greenhouse gas chemical conversion requires high-tech equipment but ensures long-term environmental benefits by minimizing the need for further disposal of by-products, reducing energy consumption, and creating secondary raw materials. Globally, this method becomes an important component not only in combating greenhouse gas emissions but also in forming closed industrial carbon cycles.

3.3.4. Utilization with microalgae

The utilization of greenhouse gases using microalgae is regarded as one of the most environmentally compatible and sustainable technologies. CO_2 biofixation through photosynthesis is not only an example of a natural emission reduction mechanism but also a comprehensive platform for carbon transformation into secondary biomass suitable for bioenergy, agriculture, or biomaterial production. Unlike chemical or thermochemical technologies, microalgae-based methods have a minimal carbon footprint at all stages from CO_2 absorption to the final product directly correlating with several key green chemistry principles.

Primarily, this technology fully realizes the principle of renewable feedstock use, as CO_2 is sourced from the environment or industrial emissions, and the main energy input is sunlight. This aligns with the “carbon cycling” concept, wherein carbon is not extracted from underground reservoirs but circulates within the biosphere. Furthermore, no toxic reagents or aggressive solvents are involved in the reaction, and the final products such as lipids, proteins, or pigments are biologically compatible. Microalgal biomass can be used as feedstock for biofuels, biofertilizers, and feed additives without generating toxic waste at any stage. This also indicates the absence of waste, since all photosynthesis products are targeted: CO_2 is absorbed, oxygen is released, and biomass accumulates. Integration of bioreactors into production systems achieves high efficiency: CO_2 absorption from flue gas reaches 80–90% per day, and wastewater treatment attains up to 70% removal of nitrogen, phosphorus, and other components.

In terms of energy efficiency, new-generation photobioreactors in closed tubular or flat-panel types ensure optimal sunlight utilization without significant energy loss. A recent case from Spain demonstrated that at CO_2 concentrations up to 10% in flue gases, fixation efficiency exceeds 1.8 kg CO_2 per kg of biomass, approaching the theoretical maximum values.

Microalgae-based systems have been successfully implemented in the Netherlands, notably in the “AlgaePARC” project, where CO_2 from gas-fired power plants is directly supplied to photobioreactors. The biomass is used to produce bioplastics, replacing petrochemical products [34]. Overall, CO_2 bioconversion by microalgae embodies virtually the entire suite of sustainable chemistry principles. Due to high flexibility and environmental safety, this technology is competitive both in energy and chemical industries, forming the foundation of “green infrastructure” in cities and industrial enterprises.

3.3.5. Direct Air Capture

Direct air capture (DAC) of CO_2 is a technologically advanced yet conceptually pivotal approach to climate change mitigation. Unlike conventional capture methods tied to point sources, DAC extracts CO_2 directly from ambient air, where its concentration is merely ≈0.04%. This renders the technology particularly suitable for densely populated regions or areas with dispersed emissions. From a green chemistry standpoint, DAC aligns with several fundamental principles, including material recyclability, conversion of hazardous substances into benign forms, reliance on renewable energy, and promotion of zero-waste processes.

In modern industrial facilities such as Orca, solid-phase CO_2 binding with aminated polymer structures occurs at ambient temperatures, while desorption takes place at approximately 100–120 °C using geothermal energy. The captured CO_2 is injected into geological formations. This process exemplifies the conversion of a mobile and reactive pollutant into a stable, environmentally benign carbonate form.

Another practical example of direct capture is the Strimech facility in the USA, operated by Carbon Engineering, where CO_2 is absorbed from air by liquid potassium hydroxide-based sorbents. After thermochemical regeneration, the captured CO_2 is used as feedstock for methanol synthesis. Thus, DAC not only reduces atmospheric CO_2 but also integrates into a circular chemical chain, enabling secondary carbon use in the fuel and chemical sectors. This methodology embodies multiple green chemistry principles simultaneously:

1. Reagent reuse for application of sorbents without waste generation;
2. Transformation of harmful substances into harmless forms, such as mineralization of CO_2 into stable carbonates;
3. Integration with renewable energy sources, in particular, geothermal or solar systems;
4. Resource efficiency, which means elimination of the need for raw material extraction.

The DAC technology also lacks toxic by-products requiring special handling, making it virtually waste-free. This allows the method's application in ecologically sensitive areas, such as northern regions of Iceland or Scandinavia, where natural conditions impose stringent environmental balance requirements. Despite the current high cost of capture (≈400–600 USD per ton of CO_2), the development of next-generation sorbents especially metal-organic frameworks, solid-phase aminopolymers, and biopolymer membranes promises cost reduction and technology scaling. This elevates DAC to the category of strategic systems essential for achieving carbon neutrality goals [35].

3.4 Greenhouse gas disposal methods correspondence to the principles of “green chemistry”

Within the scope of this study, a comparative analysis of five greenhouse gas (GHG) utilization technologies was conducted. The primary focus was placed on three key criteria: compliance with the principles of green chemistry, prevalence of industrial application, and environmental efficiency. The evaluation of effectiveness was performed using an adapted MCDA-LCA methodology (Table 3.4). This approach enables a comprehensive assessment of the impact of each technology, considering indicators such as carbon footprint, energy efficiency, toxicity of residues, material circularity, and degree of ecosystem integration.

Table 3.4

Summary comparison of greenhouse gases conversion

Technology Name	Compliance with Green Chemistry Principles	Industrial Usage Prevalence	Environmental Efficiency, Score
Thermochemical Methane Conversion	Waste reduction, atom economy, synthesis safety	Medium (production of H_2, nanomaterials)	7.8
Chemical Conversion of GHGs	Atom economy, toxicity minimization, reuse	High (chemical industry, syngas, methanol)	7.5

Photocatalytic Conversion	Renewable energy sources, waste-free, environmental cleanliness, safety, low temperatures	Low (mostly experimental or pilot facilities)	9.2
Biological Conversion (Archaea)	Biocompatibility, low temperatures, ecosystem integration	Low (laboratory and pilot scales)	8.3
Microalgae	Sustainable CO_2 cycle, solar energy, multifunctionality of biomass	Medium (biofuel, water treatment, fertilizers)	9.0
Direct Air Capture (DAC)	Waste-free, renewable energy, closed sorption cycle	Low (high cost, implemented only in select countries)	8.6

According to the evaluation results, the highest environmental efficiency scores were obtained by photocatalytic conversion (9.2) and microalgae utilization (9.0). Both technologies demonstrate strong compliance with the principles of green chemistry, particularly through the use of renewable energy sources, absence of toxic by-products, and the potential for carbon compound reuse.

The direct air capture (DAC) method, despite its limited industrial deployment, shows promising environmental performance (8.6) due to its waste-free nature and capability to fix CO_2 in a stable form. Meanwhile, chemical and thermochemical conversions remain more widespread at the industrial scale but exhibit lower environmental ratings (7.5–7.8), primarily owing to higher energy consumption and the generation of carbon monoxide as a by-product. Biological conversion involving microorganisms received an intermediate score (8.3), attributable to its environmental cleanliness but currently limited effectiveness in large-scale applications.

Thus, the analysis confirms that contemporary green approaches to greenhouse gas utilization possess not only theoretical but also practical potential, and their environmental efficiency is closely linked to adherence to key green chemistry principles. This provides a foundation for reorienting industrial processes towards a sustainable carbon balance.

3.5 Conclusion to Chapter 3

This chapter identifies that the most environmentally efficient greenhouse gas utilization methods are those that combine minimal energy consumption, absence of toxic by-products, potential for reagent reuse, and reliance on renewable energy sources. Among these, photocatalytic and biological methods exhibit the greatest potential for enabling a sustainable carbon cycle. To ensure an objective comparison of available technologies, an adapted MCDA-LCA framework was applied, integrating both quantitative metrics and qualitative sustainability indicators. The assessment results indicate that technology selection should consider not only technical performance, but also alignment with ecological sustainability principles, as these are critical for developing carbon-neutral production strategies.

CONCLUSIONS

Rising greenhouse gas emissions, particularly CO_2 and CH_4, and intensifying global climate change highlight the need to develop scientifically sound, environmentally safe, and energy-efficient technologies for their utilization. In this context, methods that comply with the principles of green chemistry and can be integrated into modern production processes are of particular importance. This work compares greenhouse gas disposal methods based on a multi-criteria analysis that takes into account environmental, energy, and technological characteristics, and experimentally investigates the effectiveness of photocatalytic CO_2 conversion. The processes of thermochemical decomposition of methane, chemical and photocatalytic conversion of CO_2, biological fixation with the involvement of microalgae, and direct CO_2 capture from the atmosphere were theoretically analyzed. The methods considered include reactions under high temperatures, catalytic reductions with the formation of valuable products, biosynthetic cycles, and absorption processes under atmospheric conditions. Photocatalytic conversion of CO_2 and CH_4 was studied experimentally at temperatures of 500–800 °C using catalysts based on γ-Al_2O_3 modified with nickel, cobalt, and iron. Ni and Co catalysts showed the highest efficiency, providing up to 99% conversion. Environmentally significant results include the absence of toxic by-products, the formation of graphitic carbon as a stable form of carbon fixation, and the generation of synthesis gas suitable for further use.

The MCDA-LCA (Multi-Criteria Decision Analysis – Life Cycle Assessment) methodology made it possible to evaluate each method according to integral indicators. The impact on global warming, energy consumption, toxicological safety, reuse of reagents, compliance with green chemistry principles, scalability, and the degree of valuable product formation were taken into account. Each indicator was evaluated on a 10-point scale, after which a weighted rating was formed. The highest rating (10/10) was given to bioconversion using microalgae, which provides natural CO_2 removal, biomass formation, and the possibility of integration into water treatment systems. The method is environmentally friendly but dependent on stable conditions and has high equipment costs.

Photocatalysis (9/10) proved to be the best in terms of environmental feasibility, energy efficiency, and technological flexibility. It does not require toxic reagents, allows the use of solar energy, has low residue formation, and provides secondary raw materials. Thermochemical conversion of methane (8/10) is effective in terms of hydrogen and carbon production, but is characterized by high process temperatures and sensitivity to catalyst stability. Chemical conversion of CO_2/CH_4 (7/10) produces methanol and other useful substances, but requires significant energy and technical resources. Direct Air Capture (DAC) received the lowest rating (6/10) due to the low concentration of CO_2 in the air, the need for large amounts of energy to regenerate sorbents, and limited profitability.

From a green chemistry perspective, the most suitable method is photocatalysis: it demonstrates atom economy, does not produce hazardous by-products, allows for the reuse of catalysts, and uses renewable energy. In contrast, DAC does not currently meet the key principles of green chemistry due to its excessive energy consumption, limited sorbent efficiency, and lack of value-added end products. Thus, the most environmentally sound method of greenhouse gas disposal is photocatalytic CO_2 conversion, which combines efficiency, environmental safety, and potential for practical implementation. The method that currently does not meet the environmental criteria for sustainable development is direct atmospheric CO_2 capture (DAC).

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